# FINAL
# REMEDIAL PROCESS OPTIMIZATION REPORT FOR OPERABLE UNIT No. 1 HILL AIR FORCE BASE, UTAH

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# EXECUTIVE SUMMARY

This report describes the application of the remedial process optimization (RPO) approach, as presented in the *RPO Handbook* (AFCEE and Air Force Base Conversion Agency [AFBCA], 1999). Parsons Engineering Science, Inc. (Parsons ES) is field-testing the approach described in the RPO handbook at multiple Air Force sites, including Operable Unit 1 (OU1) groundwater located in the eastern portion of Hill Air Force Base (Hill AFB), Utah. The Air Force goals for the RPO program are to: 1) assess the effectiveness of particular remedial actions; 2) enhance the efficiency of the remedial actions examined; and 3) when possible, identify annual operating, maintenance, and monitoring (OM&M) cost savings in excess of 20 percent for each system evaluated.

The remedies for OU1 in the ROD for Hill AFB OU1 (Environmental Management Directorate [EMD], 1998) have not yet been fully implemented. Therefore, the RPO evaluation at Hill AFB OU1 did not include some of the standard activities normally completed as part of an RPO project (e.g., examining the effectiveness and efficiency of existing remediation systems). Rather, the activities completed for the OU1 RPO evaluation included reviewing the Performance Standard Verification Plan (PSVP) for OU1 (CH2M Hill, 1999a), which describes protocols for monitoring and evaluating remediation activities at Hill AFB, and making recommendations for its refinement; evaluating groundwater monitoring data for Hill AFB OU1 utilizing the MAROS software tool (GSI, 1999), and using the results of the evaluation to generate comments to the LTMP for OU1; and providing comments regarding the MAROS tool in Parsons ES's capacity as a software beta tester for the tool. To accomplish these goals, the following tasks were completed at Hill AFB OU1:

- Review existing data to evaluate previously completed site characterization activities;
- Prepare a site-specific work plan describing the implementation of RPO;
- Evaluate the remedial decision process leading to the current system design, in accordance with the draft final RPO handbook;
- Critically review the Performance Monitoring and Performance Evaluation sections of the PSVP (CH2M Hill, 1999a);
- Evaluate the existing groundwater monitoring network at OU1, and provide recommendations for its optimization;
- Beta-test the MAROS software developed by GSI to analyze plume stability and trends in contaminant concentrations for use in refining the LTMP; and
- Prepare a site-specific RPO report presenting Parsons ES's recommendations for modifications to the PSVP and the LTMP at Hill AFB OU1.

The RPO evaluation recommendations for modification of the Internal Draft PSVP (CH2M Hill, 1999a) include suggested text for inclusion in the PSVP regarding procedures and methodologies for statistical evaluations of groundwater monitoring data.

The text, suggested for incorporation into the Internal Draft PSVP, is provided in Appendix B, and includes descriptions of statistical methods and procedures to be used in evaluating long-term monitoring data. The Base recognized some of these deficiencies and contracted the services of a statistician to develop data evaluation methodologies for inclusion in a revised PSVP.

Utilization of the MAROS tool to evaluate the contaminant plumes in OU1 provided better insight into the concentration trends in the aquifers. The complex hydrogeologic nature of the aquifers resulted in conditions that proved difficult for any statistical analytical method. The MAROS Users Manual provided good documentation of the software in an easy step-by-step manner. The software tool is intended to be used by facility managers to track performance of the remedial actions, and as such – it is a valuable tool. While the learning curve for the software is small and utility of the tool significant, the RPO evaluation of the MAROS tool identified the following items that should be reviewed prior to widespread distribution and use by the United States Air Force (USAF):

- Parsons ES personnel experienced difficulties importing data into the software, and ultimately reformatted the data as Access® ERPMIS files for use in MAROS. Re-formatting the data was a time-consuming process because the Access® ERPMIS format includes 4 tables with approximately 20 parameters each, while the EXCEL® format includes a single table with about 8 parameters.

- MAROS requires the designation of each well within a particular analysis as a "source" or "tail" well. While this information is important for the analysis, entering this information was a time-consuming step. For Hill AFB OU1, these designations were made only after searching through available plume maps for the locations of wells within the plume. It can be difficult to determine whether particular wells (such as background wells that are upgradient of the source or otherwise outside the plume boundary) should be designated as a "source" or "tail" location.

- MAROS results generated using the Mann-Kendall trend analyses were ambiguous in several cases. For example, the results from the Mann-Kendall analysis for TCE in four wells completed in zone A1 indicated that four different trends (No Trend, Decreasing, Probably Decreasing, and Stable) were present, depending upon the well. However, TCE concentrations in all four wells were below detection limits ("Not Detected") through the monitoring history of the wells. Even after consulting the user's manual, it was difficult to determine if this was a manifestation of a program bug, or if the program was applying different criteria to the four wells, leading to different results for each well.

- MAROS generates useful output summaries of results for each analysis (linear regression, Mann-Kendall, sampling optimization, etc.). However, these output reports cannot easily be saved to another file for reference at a later time. The entire analysis must be re-completed in order to generate a new set of reports. MAROS would be more user-friendly if the summary reports could be stored with the archived input data, so that additional simulations would not be necessary.

- The relatively small number of constituents (five) and wells (forty) that can be evaluated in a single analysis is a significant limitation of the MAROS software. The limit of five chemicals can be bypassed by simply repeating the analysis with a different set of chemicals. However, the limit of 40 wells, as necessary for the Mann-Kendall test, is more problematic. For areas with more than 40 wells (e.g., zone S1 at OU1 with approximately 60 wells), the wells to be used in the evaluation must be pre-selected in advance of analysis. The monitoring locations cannot be divided into two or more groups, as this will affect the results of the spatial analysis. The well pre-selection process can be time-consuming, and the decision criteria used in selecting a subset of monitoring points may differ from or conflict with the MAROS methodology.

- MAROS requires that sampling dates for all wells in a sampling event be identical, otherwise the program does not recognize them as belonging to a single sampling event. The program does allow the user to combine wells with different sampling dates as an event. MAROS would be more user-friendly if it recognized that sampling dates within a user-defined period (e.g., two or three weeks) may be part of the same sampling event. Currently, this issue is best addressed when the MAROS input files are formatted, and the database manager can identify the sampling events and manipulate the sampling dates (or event dates) accordingly.

In addition to the MAROS analysis, Parson ES performed a more robust temporal and geostatistical analysis, including spatial statistics. Depending on the future needs of Hill AFB, the more rigorous statistical procedures may be effectively applied to groundwater monitoring data at Hill AFB OU1. The methodologies and results of the more rigorous qualitative and Mann-Kendall temporal trend evaluation described in Section 3.2.2.2 could be incorporated into the monitoring decision trees developed for Hill AFB, and presented in the Draft PSVP. However, application of the spatial statistical technique was not successful and further attempts at spatial statistics are probably not warranted. The failure of the spatial statistical technique may be a consequence of the manner that the contaminants of concern (COCs) move in groundwater off of the bluff and into the groundwater system of the Weber River Valley (Section 2.2.5), and the apparent random nature in the spatial distribution of the COCs in groundwater at OU1.

Lastly, based on the results of the MAROS analysis (Section 3.2), it is recommended that one well (U1-177) be eliminated from the long term monitoring program at Hill OU1. In addition, the recommended sampling frequencies generated using the MAROS tool for monitoring wells completed in each of the water-bearing zones are provided in Appendix A.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| µg/L | micrograms per kilogram |
| AFB | Air Force Base |
| AFBCA | Air Force Base Conversion Agency |
| AFCEE/ERT | Air Force Center for Environmental Excellence/Technology Transfer Division |
| AMC | Air Mobility Command |
| ARARs | applicable or relevant and appropriate requirements |
| ASCE | American Society of Civil Engineers |
| ASTP | air stripper treatment plant |
| Bgs | below ground surface |
| BTEX | benzene, toluene, ethylbenzene, and xylenes |
| CAMU | Corrective Action Management Unit |
| CD | compact disk |
| CDP | Chemical Disposal Pit |
| CERCLA | Comprehensive Environmental |
| COC | contaminants of concern |
| DCA | 1,2-dichloroethane |
| DCB | dichlorobenzene |
| DCE | 1,1-dichloroethene |
| DQOs | data quality objectives |
| EMD | Environmental Management Directorate |
| ERPIMS | Environmental Resources Program Information Management System |
| ES | Engineering-Science, Inc. |
| ESD | explanation of significant difference |
| FFA | Federal Facilities Agreement |
| ft/sec | feet per second |
| FTA | Fire Training Areas |
| GC | gas chromatographic |
| GSI | Groundwater Services Inc. |
| GUI | graphical user interface |
| IRP | Installation Restoration Program |
| IWTP | Industrial Waste Transfer Point |
| LNAPL | light, nonaqueous-phase liquid |
| LTMP | long-term monitoring plan |
| MAROS | Monitoring and Remediation Optimization System |
| MCLs | maximum contaminant levels |
| MS | mass spectrometric |
| NAPL | nonaqueous-phase liquid |
| NCP | National Oil and Hazardous Substances Pollution Contingency Plan |
| NPL | National Priorities List |
| O&M | operations and maintenance |

| | |
|---|---|
| OM&M | operating, maintenance, and monitoring |
| OPS | operating properly and successfully |
| OU1 | Operable Unit 1 |
| Parsons ES | Parsons Engineering Science, Inc. |
| PCB | polychlorinated biphenyl |
| PRGs | preliminary remediation goals |
| PSVP | Performance Standard Verification Plan |
| RAOs | remedial action objectives |
| RBCA | risk-based |
| RD/RA | remedial design/remedial action |
| RI | remedial investigation |
| ROD | record of decision |
| RPO | Remedial Process Optimization |
| SARA | Superfund Amendments and Reauthorization Ac |
| SVOC | semivolatile organic compound |
| TCA | trichloroethane |
| TCB | trichlorobenzene |
| TCE | trichloroethene |
| UDEQ | Utah Department of Environmental Quality |
| US | United States |
| USAF | United States Air Force |
| USEPA | US Environmental Protection Agency |
| VOCs | Volatile organic compounds |
| WOST | waste oil storage tanks |
| WPOP | Waste Phenol/Oil Pit |

# SECTION 1

# INTRODUCTION

This document was prepared by Parsons Engineering Science, Inc. (Parsons ES) for the United States (US) Air Force Center for Environmental Excellence/Technology Transfer Division (AFCEE/ERT), as part of a delivery order under the US Air Force Air Mobility Command (AMC) contract (F11623-94-D0024, RL 72). The report describes the application of the remedial process optimization (RPO) approach, as presented in the *RPO Handbook* (AFCEE and Air Force Base Conversion Agency [AFBCA], 1999). This report presents a review of the Performance Standard Verification Plan (PSVP; CH2M Hill, 1999a) and an evaluation of the long term monitoring plan (LTMP) for Operable Unit 1 (OU1), at Hill Air Force Base (AFB), Utah. This report also provides an assessment of the Monitoring and Remediation Optimization system (MAROS) software tool (Groundwater Services, Inc. [GSI], 1999) as it applies to the evaluation of long term monitoring plans.

## 1.1 RPO APPROACH AND OBJECTIVES

The US Air Force initiated the RPO program to develop a systematic means for evaluating and improving the effectiveness and efficiency of site remediation so that maximum risk reduction is achieved for each dollar spent. The RPO process is intended to optimize remediation systems by evaluating the technical approach of *how* the cleanup will be completed, and by reviewing regulatory cleanup goals. Just as the technical approach to remediation should be upgraded from time to time to take advantage of advances in remediation practice, changes in regulatory framework, such as risk-based cleanup goals and the growing acceptance of monitored natural attenuation, also should be considered in the optimization process. An effective RPO program will examine a wide range of optimization opportunities. The Air Force goals for the RPO program are to:

- Assess the effectiveness of remedial actions in progress;
- Improve the efficiency of existing remedial systems;
- Explore regulatory options to modify remedial action objectives (if appropriate); and
- When possible, identify annual operating, maintenance, and monitoring (OM&M) cost savings in excess of 20 percent for each system evaluated.

RPO has many potential benefits, including identifying the most effective remediation options, improving tracking of remedial progress and protectiveness, reducing operating costs, optimizing monitoring systems with concomitant reductions in analytical costs, reevaluating remedial action objectives (RAOs) and cleanup goals, improving regulatory feedback, and accelerating site transfer and closure. It should be noted that not all of the activities possible in an RPO program were performed for OU1 at Hill AFB.

The RPO Phase II evaluation at Hill AFB OU1, was conducted based on guidance presented in the draft final *RPO Handbook* (AFCEE and AFBCA, 1999). The handbook describes a three-phased approach for implementing the RPO program and provides guidelines for reviewing the performance of existing remediation systems, enhancing the performance of existing systems, performing 5-year Record of Decision (ROD) reviews, and preparing documentation for "Operating Properly and Successfully" (OPS) certifications. An effective RPO program will pursue a wide range of optimization opportunities

The specific objectives of the RPO evaluation at Hill AFB OU1 and the tasks to be completed by Parsons ES under this RPO Phase II effort were presented in the *Final Work Plan for Remedial Process Optimization at Operable Unit 1, Hill Air Force Base, Utah* (Parsons ES, 1999), and are summarized below. This report presents the results of the RPO Phase II evaluation conducted at OU1.

## 1.2 SCOPE AND OBJECTIVES OF RPO AT OU1, HILL AFB

The remedies for OU1 identified in the ROD for Hill AFB OU1 (Environmental Management Directorate [EMD], 1998) have not yet been fully implemented. Therefore, the RPO evaluation at Hill AFB OU1 did not include some of the standard activities normally completed as part of an RPO project (e.g., examining the effectiveness and efficiency of existing remediation systems). Rather, the activities completed for the OU1 RPO evaluation included reviewing the PSVP for OU1 (CH2M Hill, 1999a), which describes protocols for monitoring and evaluating remediation activities at Hill AFB, and making recommendations for its refinement; evaluating groundwater monitoring data for Hill AFB OU1 utilizing the MAROS software tool (GSI, 1999), and using the results of the evaluation to generate comments to the LTMP for OU1; and providing comments regarding the MAROS tool in our capacity as a software beta tester for the tool. To accomplish these goals, Parsons ES:

- Reviewed data to evaluate previously completed site characterization and treatability study activities;
- Prepared a site-specific work plan describing the implementation of RPO at Hill AFB OU1;
- Evaluated the remedial decision process leading to the current remediation system design, in accordance with the draft final *RPO Handbook*;
- Critically reviewed the Performance Monitoring and Performance Evaluation sections of the PSVP (CH2M Hill, 1999a);
- Evaluated the existing groundwater monitoring network at OU1, and provided recommendations for its optimization;

- Beta-tested the MAROS software developed by GSI to analyze plume stability and trends in contaminant concentrations for use in refining the LTMP; and

- Prepared this site-specific RPO report describing the results of the RPO evaluation at Hill AFB OU1, and providing recommendations for modifications to the PSVP and the LTMP.

This RPO report presents an overview of environmental conditions at OU1, the existing regulatory framework, and the potential opportunities to apply the MAROS software for the RPO evaluation of the PSVP. The report consists of 5 sections, including this introduction, and one appendix. A review of the operational history, background information, and physical characteristics of Hill AFB OU1 is presented in Section 2. Section 3 provides a discussion of the PSVP and the results of statistical evaluation of groundwater monitoring data. Section 4 provides recommendations for refinements to the PSVP, suggestions for modifications to the MAROS software, and recommendations for improvements to the LTMP based on application of the MAROS tool. Section 5 provides a list of the references cited in this document. Appendix A provides example output from the MAROS tool used in the analysis.

# SECTION 2

# SITE DESCRIPTION

The following subsections briefly describe the relevant features of OU1, including the site location, contaminant source areas, geologic and hydrogeologic conditions, remediation history, and proposed remediation systems. An understanding of past and current site conditions, using available background information is necessary to accurately organize, interpret, and analyze the pertinent data for the RPO and MAROS evaluation at OU1.

## 2.1 LOCATION AND OPERATIONAL HISTORY

Hill AFB is located in northern Utah, approximately 25 miles north of Salt Lake City and 5 miles south of Ogden. Hill AFB occupies approximately 6,700 acres in Davis and Weber Counties. The western boundary of Hill AFB is approximately formed by Interstate 15, and the southern boundary by State Route 193 (Figure 2.1). The northern and northeastern perimeter is bounded by the privately owned Davis-Weber irrigation canal. The canal is located near the base of a step erosional valley formed by the Weber River (Figure 2.2).

Hill AFB has been the site of military activities since 1920. Historic activities at Hill AFB have included storage and distribution of military equipment, aircraft rehabilitation and maintenance, and missile assembly. On-Base industrial processes have included metal plating, degreasing, paint stripping, and painting – all activities associated with aircraft, missile, vehicle, and railroad locomotive maintenance and repair. These processes have used numerous chemicals, including chlorinated and non-chlorinated solvents and degreasers, petroleum distillates, acidic and basic cleansers, and metals. In the past, chemicals and waste products were disposed at the Industrial Wastewater Treatment Plant (IWTP), in chemical disposal pits and landfills, and at off-Base disposal facilities. Disposal in chemical pits and landfills was discontinued by 1980. All waste products are currently treated at the IWTP, recycled on-Base, or sent to off-Base treatment or disposal facilities.

OU1, one of nine operable units at Hill AFB, is located in the eastern portion of the Base (Figure 2.1), and occupies an area of approximately 300 acres along the high bluffs that form the southern border of the Weber River valley. The area surrounding OU1 is largely undeveloped. OU1 includes the following Installation Restoration Program (IRP) sites: Landfills 3 and 4, Chemical Disposal Pits 1 and 2, Fire Training Areas 1 and 2, and the Waste Phenol/Oil Pit. The location of each of these areas within OU1 is shown in Figure 2.2.

Characterization and monitoring of environmental conditions at OU1 began in 1976 to evaluate the nature and extent of leachate migration from Landfill 4 to the slopes of the bluff just north of OU1. In the early 1980s, IRP activities were initiated at Hill AFB, and several investigations were completed, including an IRP Phase I Records Search (Engineering Science, Inc. [ES], 1982). Since the early 1990s, Montgomery Watson (1995a) has conducted remedial investigations at OU1 under the IRP. A complete description of investigation activities and results is provided in the following reports:

- Comprehensive Remedial Investigation Report for Operable Unit 1 (Montgomery Watson, 1995a),
- Feasibility Study Report For Operable Unit 1 (Montgomery Watson, 1995b),
- Final Feasibility Study Report for Operable Unit 1 (CH2M Hill, 1998a).

## 2.2 SITE GEOLOGY AND HYDROGEOLOGY

The principal geologic and hydrogeologic features of Hill AFB OU1 are briefly described in the following sections. More comprehensive descriptions of the geology and hydrogeology of OU1 are presented in the *Final Comprehensive Remedial Investigation (RI) Report for Operable Unit 1* (Montgomery Watson, 1995a); the *Groundwater Pre-Design Report* (CH2M HILL, 1999b); and *Final Operable Unit 1 Monitoring Well Installation and Impact Assessment of South Weber No. 2 (South Weber No. 2 Investigation)* (CH2M HILL, 1998b).

The geologic units underlying OU1 consist of Recent terrace deposits, the Provo, Alpine, and Delta Formations. Other geologic and geomorphic units including landslide debris, alluvium, colluvium, and topsoil are also present throughout the area. The relationships among the geologic units present at OU1 are depicted in a diagrammatic geologic cross-section (Figure 2.3 and 2.4), and are described below.

### 2.2.1 Provo Formation

The Provo Formation is topographically the uppermost geologic unit at Hill AFB OU1 (Figure 2.3), and overlies the older Alpine Formation. The Provo Formation is situated on the large flat terrace surface on which the on-Base portions of OU1 are located. The Provo Formation consists of a heterogeneous mixture of gravel and sand, and is generally 10 to 30 feet thick. The lowermost 3 feet of this unit generally is water bearing, although the saturated thickness can range from zero to greater than 20 feet. Groundwater within the Provo Formation is unconfined and tends to move along the contact with the underlying Alpine Formation. Groundwater movement also occurs along paleochannels incised into the Alpine Formation prior to deposition of the overlying Provo Formation. The direction of groundwater movement is generally from southeast to northwest in the on-Base portions of OU1. Natural precipitation and irrigation at the golf course located southeast of OU1 are the most probable sources of recharge to groundwater. The water-bearing zone in the Provo Formation has been labeled the "S1" zone.

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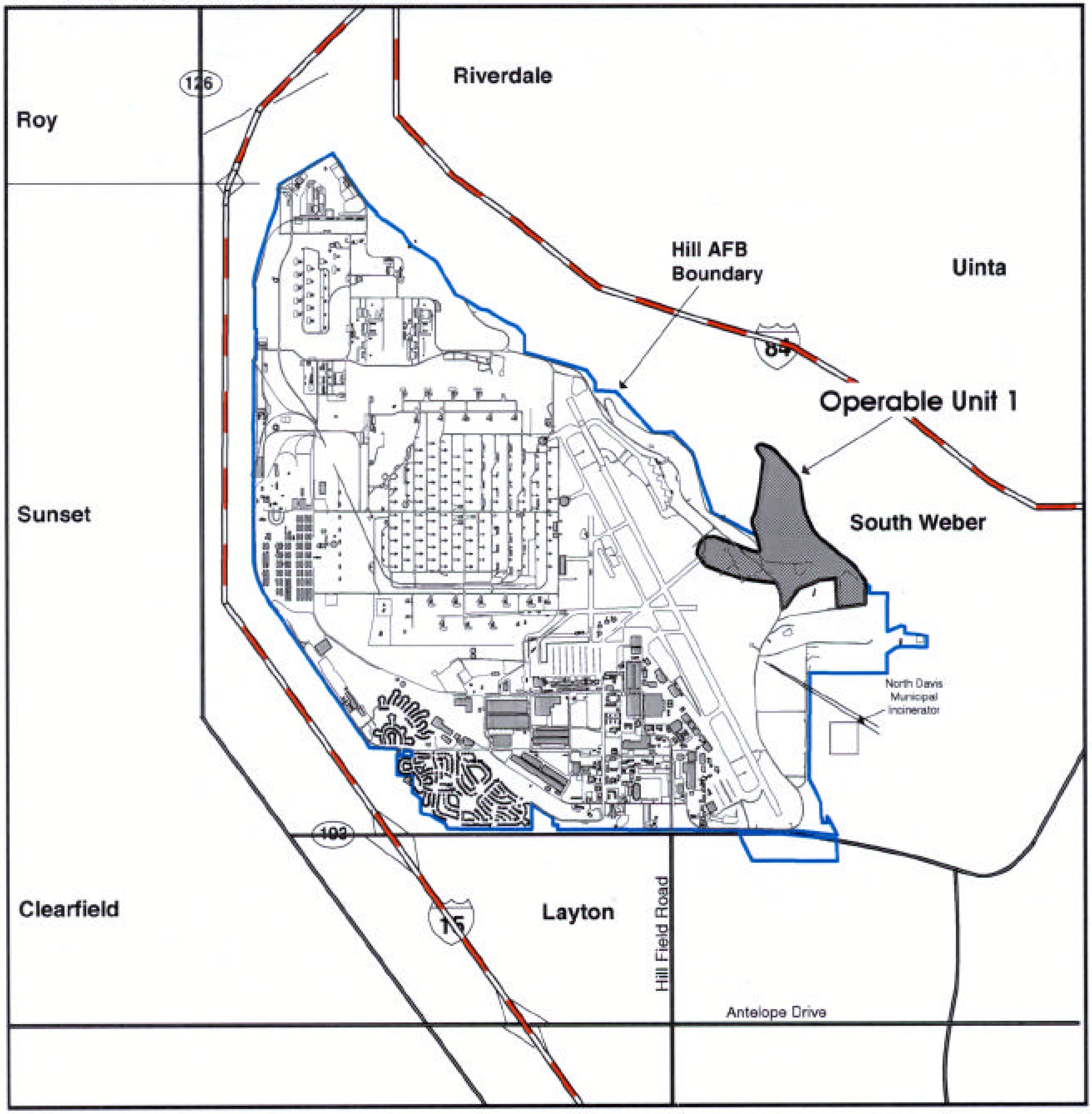
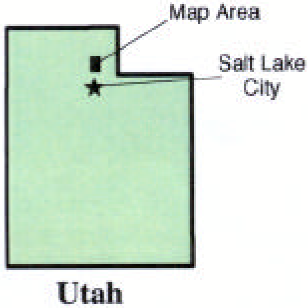
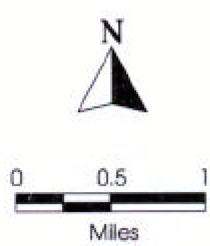



Utah




Source: CH2MHILL, 1999a.

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**FIGURE 2-1**

## LOCATION OF HILL AFB AND OPERABLE UNIT 1

Remedial Process Optimization
Hill AFB, Utah

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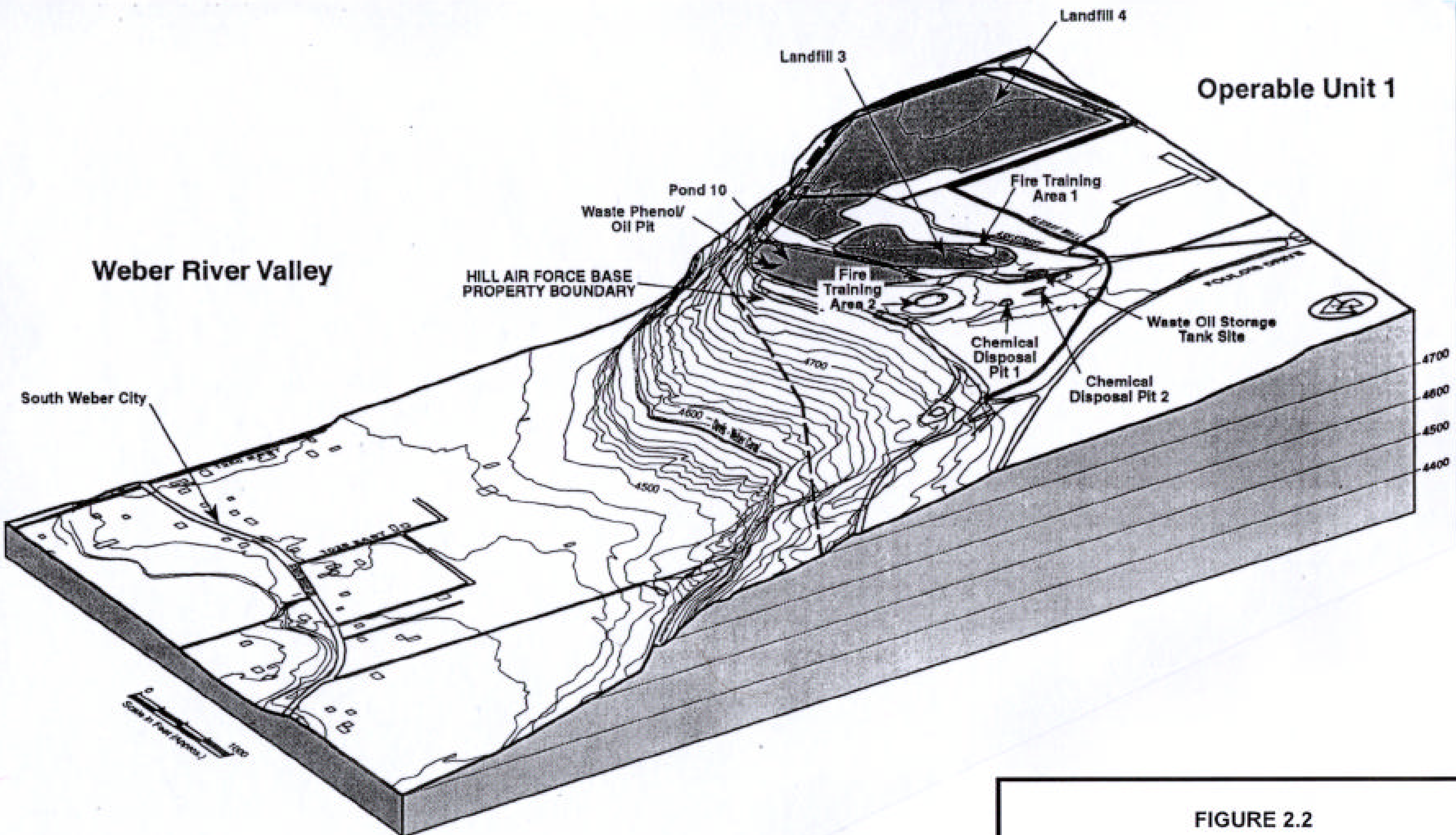


*Note: Soil excavated from the Waste Phenol/Oil Pit was placed under the clay cap of Landfill 3. Precise location of disposal within Landfill 3 is unknown.*

FIGURE 2.2

SITE LAYOUT FOR OPERABLE UNIT 1

Remedial Process Optimization
Hill AFB, Utah

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PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Source: Montgomery Watson, 1995a.

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### 2.2.2 Alpine Formation

The Alpine Formation underlies the Provo Formation throughout OU1, and is exposed on the slopes of the bluff along the northern and northeastern boundaries of the Base (Figure 2.3). The Alpine Formation is approximately 500 feet thick and overlies the drinking-water aquifer. This formation has been sub-divided into three lithologic units with six hydrologic zones. The following units have been identified:

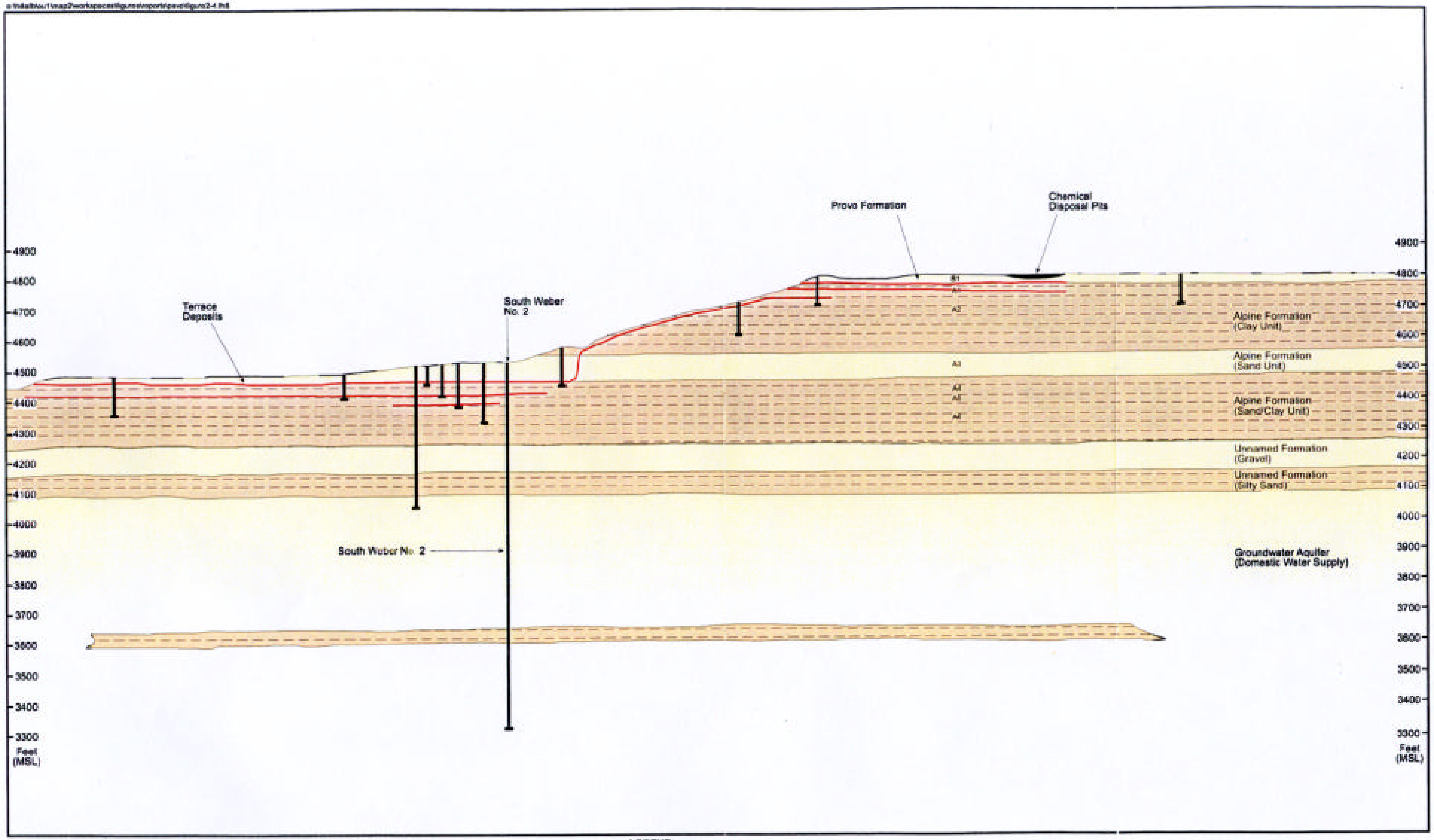
**Clay Unit**. The clay unit is located directly beneath the Provo Formation and is further broken down into upper and lower sub-units. The upper clay sub-unit consists of approximately 80 to 90 percent silty clay with interbeds of fine to very fine-grained sand comprising 10 to 20 percent of the sub-unit. The thickness of the upper clay sub-unit ranges from 10 to 25 feet. Groundwater within the upper clay sub-unit generally occurs in the thin sand interbeds. Groundwater recharge to this sub-unit is probably through the overlying Provo Formation. This water-bearing zone has been designated as the "A1" zone. Contaminants have been detected in groundwater samples from the A1 zone, but the areal extent of contaminants is considerably less than occurs in the overlying Provo Formation.

The lower clay sub-unit contains fewer sand interbeds than the upper clay sub-unit, and consists of approximately 90 to 95 percent silty clay with 5 to 10 percent sand. The thickness of this sub-unit ranges from 100 to 135 feet. The hydrogeologic characteristics of the lower clay unit are similar to the overlying upper clay unit, but groundwater is less frequently encountered in the lower clay unit, as a consequence of the few sand interbeds in the lower clay unit. The direction of groundwater movement in the lower clay unit appears to be toward the north. This water-bearing zone has been designated as the "A2" zone.

**Sand Unit**. The sand unit of the Alpine Formation underlies the clay unit and is composed primarily of fine to very fine-grained sand, with a few clay or silt interbeds. The sand unit is approximately 85 feet thick. The lack of clay or silt interbeds allows downward migration of groundwater from overlying units through the sand unit, to the underlying sand/clay unit, which inhibits further downward movement. Groundwater moves laterally to the north along the contact with the underlying sand/clay unit. Leakage from irrigation canals may be the principal source of recharge to this unit. The sand unit appears to be in hydraulic communication with the recent terrace deposits and may be a significant source of recharge to the terrace deposits. The water-bearing zone in the sand unit has been designated as the "A3" zone.

**Sand/Clay Unit**. The geologic unit occurring directly below the sand unit has been designated as the sand/clay unit of the Alpine Formation. The major part of the sand/clay unit consists of fine-grained materials; the nomenclature for the unit is in reference to the numerous interbedded sand layers. Groundwater within the sand/clay unit occurs within fine to medium-grained sand interbeds.

Three distinct water-bearing zones, designated as the "A4," "A5," and "A6" water-bearing zones, have been identified in the sand/clay unit. Groundwater within these water-bearing zones probably occurs under confined conditions, because the static elevations of water measured in wells completed in these zones are well above the screened intervals of the wells. The "A4" water-bearing zone is composed of a series of




Notes:

1) Alpine Formation/Groundwater Aquifer contact can be extrapolated to domestic supply wells near the southeast corner of Hill Air Force Base.
2) Selected exploration points shown in the cross-section are the deepest exploration points in the area.
3) No vertical exaggeration.

**LEGEND**

- Fine-grained Materials
- Coarse-grained Materials
- Approximate Location of Groundwater Contamination
- Exploration Point

Source: CH2MHILL, 1999a.

**FIGURE 2-3**

**GENERALIZED GEOLOGIC CROSS-SECTION**

Remedial Process Optimization
Hill AFB, Utah

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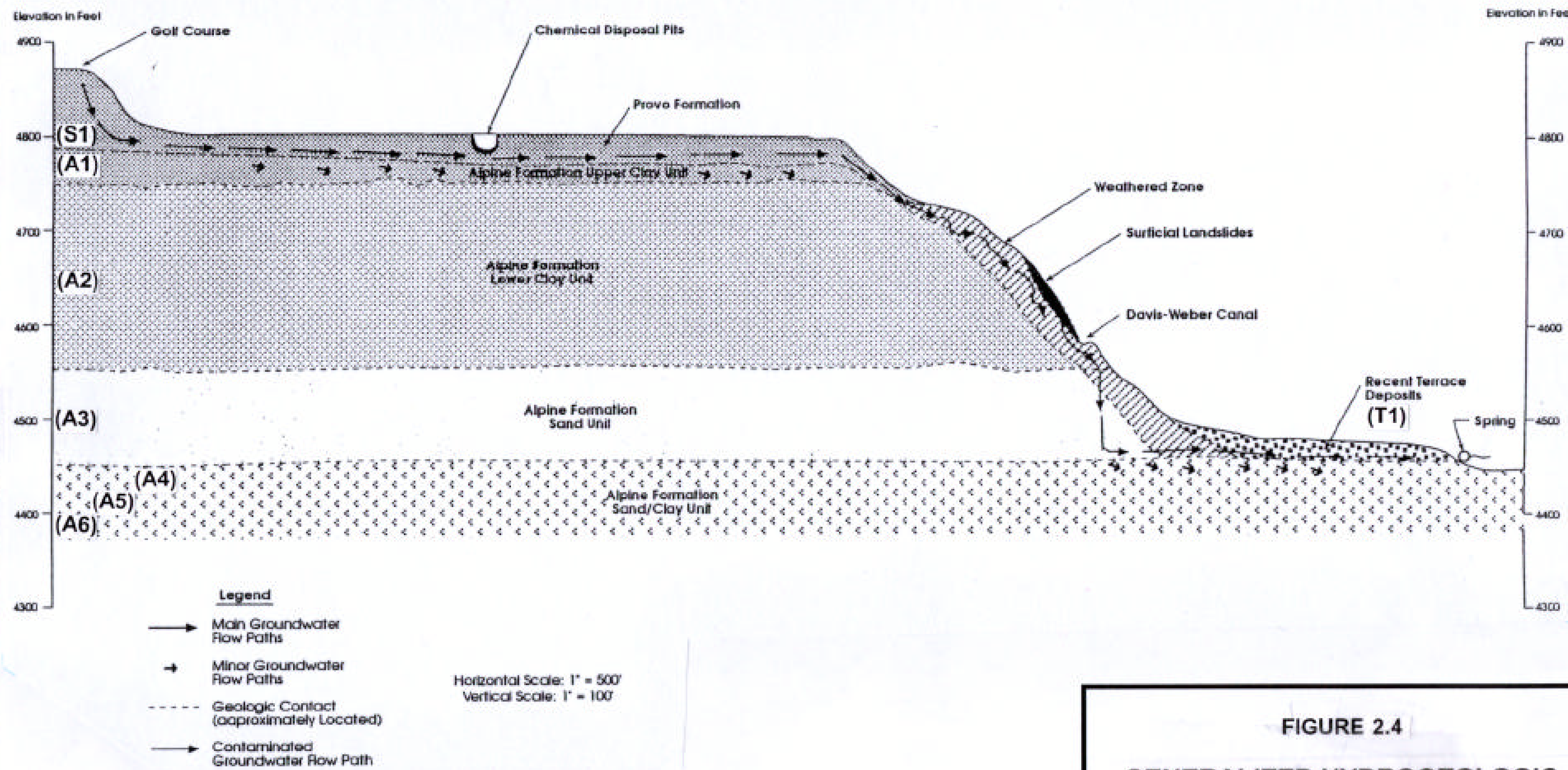


FIGURE 2.4

**GENERALIZED HYDROGEOLOGIC CROSS-SECTION**

Remedial Process Optimization
Hill AFB, Utah

**PARSONS**
**PARSONS ENGINEERING SCIENCE, INC.**
Denver, Colorado

Source: Environmental Management Directorate, 1998.

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thin, fine-grained sand and gravel layers in a silty sand matrix. The permeability of the fine-grained material comprising the “A4” zone is apparently low, and the yield of water from this zone is poor. The "A5" water-bearing zone consists of a 10-foot thick layer of medium to coarse-grained sand. The "A6" water-bearing zone is composed of a series of thin, fine-grained sand and gravel layers in a silty sand matrix. The yield of water from both the "A5" and "A6" zones is considered good.

### 2.2.3 Recent Terrace Deposits

Terrace deposits of Recent age occur in that portion of OU1 located north of the Base boundary along the valley floor of the Weber River (Figure 2.3). The terrace deposits are composed primarily of unconsolidated fluvial sands and gravel with interbedded silty strata. Groundwater occurs in the recent terrace deposits where they are in contact with the sand/clay unit of the Alpine Formation. The water-bearing zone, identified as the "T1" zone, is considered to be unconfined (Figure 2.4). The terrace deposits are apparently in direct hydraulic communication with the A3 water-bearing zone in the sand unit of the Alpine Formation (Figure 2.4) and is sometimes referred to as the T1/A3 zone. Groundwater recharge to the terrace deposits appears to occur primarily from the sand unit. The direction of groundwater flow in the terrace deposits is generally north toward the Weber River. In places, the water-bearing zone in the terrace deposits appears to discharge from the terrace slope as a series of springs at the toe of the slope. The hydraulic gradient in the terrace deposits is relatively flat except near the springs at the toe of the slope, where the gradient increases.

### 2.2.4 Delta Formation

The groundwater aquifer used for drinking water occurs in the Delta Formation at a depth of approximately 350 feet below ground surface (bgs) in the Weber River Valley (Figure 2.3 and 2.4). The Delta or groundwater aquifer is composed primarily of sand, with gravel lenses and some boulders. Based on the specific capacity of production wells completed in the aquifer, the permeability of the groundwater aquifer is presumed to be very high. A monitoring well (U1-197) was recently installed in the groundwater aquifer to enable long-term monitoring of the Delta aquifer.

### 2.2.5 Hydraulics of Groundwater System at Hill AFB OU1

Recharge to the groundwater system at Hill AFB OU1 begins with infiltration of precipitation (and golf-course irrigation water) through the surface soil and the unsaturated upper part of the Provo Formation (Figure 2.3). Water saturates zone S1 in the lower part of the Provo Formation, at the contact with the underlying clay unit that forms the upper part of the Alpine Formation (Montgomery Watsonl, 1995a). Some water moves vertically into the upper clay unit of the Alpine Formation, but the rate of movement of water into the clay is extremely low, because the vertical hydraulic conductivity of the clay unit is low. Consequently, groundwater movement in the S1 saturated zone at the base of the Provo Formation is primarily horizontal, toward the edge of the escarpment that forms the northern and northeastern perimeter of Hill AFB.

In general, the direction of groundwater movement at OU1 is to the north off the bluff, but flow off the bluff does not occur uniformly along the edge of the escarpment. Groundwater that reaches the escarpment edge moves downslope through the thin veneer of soil that blankets the escarpment, or through other pathways near the surface of the escarpment. Several paleochannels, incised into the Alpine Formation clays, are present beneath the edge of the escarpment. These paleochannels are filled with saturated sand and gravel, and are the most transmissive zones underlying OU1. They represent pathways for the preferential movement of groundwater off the bluff.

Most groundwater in the upper water-bearing zones (zones S1, A1, A2, and A3/T1 [see Section 2.2.3]) at Hill AFB OU1 appears to move off the bluff in areas where incised paleochannels intersect the escarpment, and continues downslope along preferential flowpaths through the veneer of sediments on the escarpment of the bluff. These flowpaths may include the contact between the sedimentary veneer and the unweathered clay of the Alpine Formation, landslide deposits and failure planes, and rubble on the hillside. When groundwater moving down the escarpment encounters slumped earth material, slide planes, or other zones of higher permeability, it may reach the ground surface as seeps on the escarpment, or as springs near the toe of the escarpment slope.

Probably only a small part of the groundwater originating on the Base is discharged as springs or seeps. Most groundwater moves off of the escarpment in the subsurface, discharges into the upper, unconfined T1 groundwater system in the Weber River Valley, and mixes with groundwater in the off-Base groundwater system (Figure 2.4). Percolation of precipitation, infiltration of irrigation water, and seepage losses from the Davis-Weber Canal, also represent sources of recharge to the off-Base groundwater system. Groundwater movement in the off-Base system is to the north, toward the axis of the Weber River Valley.

The horizontal hydraulic gradient of the groundwater system at OU1 is a function of the topography and the hydraulic conductivity of the saturated earth materials. The gradient is relatively flat on the upper surface of the bluff in OU1, and in the Weber River Valley, as a consequence of the flat topography in these areas. Where groundwater moves off-Base and into the veneer of unconsolidated materials along the escarpment of the Weber River Valley, the hydraulic gradient becomes steeper, as a consequence of the steep slope of the escarpment and the generally lower hydraulic conductivity of the sediments in this area.

Vertical hydraulic gradients between vertically-juxtaposed water-bearing zones are generally directed downward, indicating that groundwater movement from the uppermost saturated zone (S1 in the Provo Formation) to deeper water-bearing zones can occur (CH2M Hill, 1995). However, the values of hydraulic conductivity for the clay and silt units that separate the various water-bearing zones are several orders of magnitude lower than the values of hydraulic conductivity of the water-bearing zones (which typically consist of sand with minor gravel); and the velocity of groundwater movement downward through the silt and clay units is correspondingly low. Therefore, the primary component of groundwater movement at Hill AFB OU1 is in the horizontal plane within the different water-bearing zones. The low values of vertical hydraulic conductivity limit hydraulic communication among the various water-bearing zones, so that individual water-bearing zones generally function as separate hydrostratigraphic units (CH2M Hill, 1995).

## 2.3 NATURE AND EXTENT OF CONTAMINATION

OU1 has been divided into source areas and non-source areas. The disposal sites that are the source of contaminants at OU1 are considered to be source areas. The non-source areas are the plumes of contaminated groundwater emanating from source areas. Contaminated groundwater underlying the source areas is considered part of the source areas.

### 2.3.1 Source Areas

OU1 source areas include Landfills 3 and 4, Chemical Disposal Pits (CDP) 1 and 2, Fire Training Areas (FTA) 1 and 2, the Waste Phenol/Oil Pit (WPOP), the Waste Oil Storage Tanks (WOST), the light non-aqueous phase liquid (LNAPL) plume, and the contaminated groundwater below the source areas. The locations of the OU1 source areas are shown on Figure 2.2 and are briefly described below.

- **Landfill 3:** An industrial (dump and burn) liquid and solid waste disposal site in operation from 1940 through 1967. The landfill area was covered with a low-permeability cap of compacted soil in 1985 and 1986 to reduce surface infiltration.

- **Landfill 4:** A sanitary refuse landfill in operation from 1967 through 1973. The landfill area was covered with a low-permeability cap of compacted soil in 1985 to reduce surface infiltration.

- **Chemical Disposal Pits 1 and 2:** An industrial liquid waste disposal site in operation from 1952 through 1973.

- **Fire Training Area 1:** A fire-training practice area used by Hill AFB from the mid-1950s through 1973 to extinguish simulated aircraft fires.

- **Fire Training Area 2:** A fire-training practice area used by Hill AFB from 1973 until 1995 to extinguish simulated aircraft fires.

- **Waste Phenol/Oil Pit:** A brick-lined pit used periodically from 1954 through 1965 to dispose and burn waste oil and phenol.

- **Waste Oil Storage Tanks:** A series of four tanks used from the mid-1960s through 1981 to store waste oil. The tanks were decommissioned and removed in 1981.

- **Light Non Aqueous Phase Liquid Plumes**: Two LNAPL layers on the shallow groundwater table extend northwest from Fire Training Area 1 and westward from the CDP areas. The LNAPL plumes are composed primarily of jet fuel.

### 2.3.2 Non Source Areas

The non-source areas consist of contaminated groundwater emanating from source areas in OU1. Two extensive plumes of contaminated groundwater, designated as the Off-Base Plume and the Western Plume, have been identified at OU1. The primary contaminant of concern in the non-source area groundwater plumes is cis-

1,2-dichloroethene (DCE). Natural attenuation of contaminants appears to be occurring in the on-Base and off-Base plumes.

### 2.3.3 Contaminants in OU1 Groundwater and Spring Water

Baseline conditions in groundwater and spring water at OU1 are considered to be the initial conditions that will be used to evaluate the future performance of the remediation systems. A more complete description of baseline conditions and current contamination conditions at Hill AFB OU1 is presented in the *Groundwater Pre-Design Report* (CH2M Hill, 1999b).

Baseline conditions were developed for groundwater and spring water, but were not developed for soil because remediation of soil is not included as part of current remedial actions at OU1. Soil conditions at OU1 have been thoroughly described in the *RI* (Montgomery Watson, 1995a), and the *Groundwater Pre-Design Report* (CH2M Hill, 1999b).

The contaminant conditions in groundwater at OU1 are distinctly different among the various water-bearing units present at the site. The following discussion of the nature and extent of contaminants in groundwater at OU1 is based on data from the seventeenth round of groundwater sampling, completed during the late Spring of 1998, and used to develop baseline conditions. The seventeenth groundwater sampling round is further described in the *Analytical Data Report for the Seventeenth Groundwater Sampling Round at Operable Unit 1* (CH2M HILL, l999c). Data from this round were also presented in the *Groundwater Pre-Design Report* (CH2M Hill, 1999b).

#### 2.3.3.1 Provo Formation (S1) Groundwater

The principal contaminants that have been detected in the Provo Formation S1 water-bearing zone are chlorinated solvents and petroleum fuel constituents (Table 2.1). DCE and vinyl chloride, detected at concentrations ranging to 8,600 micrograms per liter (μg/L) and 2,400 μg/L, respectively, are the most widespread contaminants; and the areal extent of DCE and vinyl chloride in groundwater of the S1 zone is generally similar. Numerous other compounds have been detected in the S1 water-bearing zone, including several contaminants at concentrations that exceed their respective maximum contaminant level concentrations (MCLs); but the areal extent of all other compounds in S1 groundwater is encompassed within the limits of the DCE and vinyl chloride plumes. Other chlorinated organic compounds found in the S1 water-bearing zone include trichloroethene (TCE), at concentrations ranging up to 2,400 μg/L, and chlorinated benzenes at concentrations ranging up to 160,000 μg/L. The highest concentrations of benzene, toluene, and xylene compounds are associated with the LNAPL plumes emanating from the CDPs and FTA 1.

The occurrence and distribution of other, less significant groundwater contaminants, including semi-volatile organic compounds (SVOCs), metals, pesticides, herbicides, polychlorinated biphenyl compounds (PCBs), explosives, and radionuclides, are described in more detail in the *Groundwater Pre-Design Report* (CH2M Hill, 1999b).

**TABLE 2.1**
**CONSTITUENTS OF POTENTIAL CONCERN DETECTED IN GROUNDWATER**
**REMEDIAL PROCESS OPTIMIZATION, OU1**
**HILL AIR FORCE BASE, UTAH**

**Monitoring Zone S1**

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L)[a/] Minimum | Detection Limits (µg/L)[a/] Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum c/ | PRG[b/] (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 271 | 93 | 25.5 | 63 | 27 | 42.9 | 0.1 | 1200 | 0.2 | 1700 | 5 |
| Toluene | 164 | 199 | 54.8 | 61 | 40 | 65.6 | 0.2 | 5000 | 0.11 | 2400 | 1,000 |
| Chlorobenzene | 164 | 199 | 54.8 | 61 | 37 | 60.7 | 0.1 | 5000 | 0.1 | 5000 | 100 |
| 1,1-Dichloroethane | 192 | 172 | 47.3 | 63 | 40 | 63.5 | 0.08 | 5000 | 0.4 | 4300 | 790 |
| 1,2-Dichloroethane | 304 | 59 | 16.3 | 63 | 23 | 36.5 | 0.09 | 5000 | 0.3 | 180 | 5 |
| cis-1,2-Dichloroethene | 54 | 175 | 76.4 | 50 | 40 | 80.0 | 0.1 | 5000 | 0.3 | 8600 | 70 |
| trans-Dichloroethene | 202 | 31 | 13.3 | 52 | 18 | 34.6 | 0.1 | 5000 | 0.12 | 32 | 100 |
| 1,2-Dichlorobenzene | 129 | 244 | 65.4 | 61 | 44 | 72.1 | 0.1 | 5000 | 0.1 | 160000 | 600 |
| 1,3-Dichlorobenzene | 235 | 115 | 32.9 | 62 | 32 | 51.6 | 0.1 | 5000 | 0.12 | 1800 | -[d/] |
| 1,4-Dichlorobenzene | 135 | 241 | 64.1 | 62 | 41 | 66.1 | 0.1 | 5000 | 0.17 | 12000 | 75 |
| 2,4-Dimethylphenol | 40 | 14 | 25.9 | 46 | 11 | 23.9 | 1.4 | 1000 | 4.02 | 310 | 600 |
| Ethylbenzene | 213 | 128 | 37.5 | 63 | 33 | 52.4 | 0.1 | 5000 | 0.12 | 120 | 700 |
| 4-Methylphenol | 38 | 16 | 29.6 | 45 | 13 | 28.9 | 1.8 | 1000 | 2.21 | 1200 | 1,500 |
| Tetrachloroethene | 79 | 9 | 10.2 | 64 | 9 | 14.1 | 0.03 | 5000 | 0.3 | 2.7 | 5 |
| 1,2,3-Trichlorobenzene | 214 | 21 | 8.9 | 52 | 15 | 28.8 | 0.1 | 5000 | 0.1 | 4500 | - |
| 1,2,4-Trichlorobenzene | 247 | 86 | 25.8 | 57 | 23 | 40.4 | 0.1 | 5000 | 0.3 | 26000 | 70 |
| 1,1,1-Trichloroethane | 299 | 111 | 27.1 | 63 | 25 | 39.7 | 0.09 | 5000 | 0.3 | 3000 | 200 |
| Trichloroethene | 262 | 109 | 29.4 | 61 | 34 | 55.7 | 0.1 | 5000 | 0.23 | 2400 | 5 |
| Vinyl Chloride | 169 | 202 | 54.4 | 63 | 35 | 55.6 | 0.2 | 10000 | 0.4 | 2400 | 2 |
| Xylenes | 66 | 81 | 55.1 | 50 | 29 | 58.0 | 1 | 5000 | 0.81 | 4800 | 10,000 |
| Meta- and Para- Xylene | 102 | 96 | 48.5 | 50 | 26 | 52.0 | 0.2 | 250 | 0.2 | 580 | 750 |
| Ortho-Xylene | 98 | 107 | 52.2 | 52 | 28 | 53.8 | 0.1 | 250 | 0.11 | 240 | 600 |

**Monitoring Zone A1**

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 103 | 26 | 20.2 | 19 | 7 | 36.8 | 0.1 | 500 | 0.1 | 78.3 | 5 |
| Toluene | 83 | 42 | 33.6 | 19 | 14 | 73.7 | 0.2 | 500 | 0.085 | 200 | 1,000 |
| Chlorobenzene | 94 | 36 | 27.7 | 19 | 9 | 47.4 | 0.1 | 500 | 0.1 | 1950 | 100 |
| 1,1-Dichloroethane | 92 | 44 | 32.4 | 19 | 7 | 36.8 | 0.08 | 500 | 0.3 | 84 | 790 |
| 1,2-Dichloroethane | 116 | 16 | 12.1 | 19 | 5 | 26.3 | 0.09 | 500 | 0.4 | 4.9 | 5 |
| cis-1,2-Dichloroethene | 33 | 61 | 64.9 | 18 | 11 | 61.1 | 0.1 | 500 | 0.14 | 5000 | 70 |
| trans-Dichloroethene | 80 | 19 | 19.2 | 18 | 5 | 27.8 | 0.1 | 500 | 0.2 | 8.5 | 100 |
| 1,2-Dichlorobenzene | 87 | 43 | 33.1 | 19 | 9 | 47.4 | 0.1 | 5000 | 0.1 | 36700 | 600 |
| 1,3-Dichlorobenzene | 115 | 13 | 10.2 | 19 | 5 | 26.3 | 0.1 | 500 | 0.3 | 446 | - |
| 1,4-Dichlorobenzene | 94 | 37 | 28.2 | 19 | 8 | 42.1 | 0.1 | 500 | 0.13 | 3200 | 75 |
| 2,4-Dimethlyphenol | 23 | 2 | 8.0 | 22 | 2 | 9.1 | 1.8 | 100 | 3.7 | 570 | 600 |
| Ethylbenzene | 114 | 17 | 13.0 | 19 | 5 | 26.3 | 0.1 | 500 | 0.3 | 36 | 700 |
| 4-Methylphenol | 22 | 1 | 4.3 | 22 | 1 | 4.5 | 1.8 | 10 | 32 | 32 | 1,500 |
| Tetrachloroethene | 40 | 0 | 0.0 | 30 | 0 | 0.0 | 0.1 | 25.1 | ND | ND | 5 |
| 1,2,3-Trichlorobenzene | 105 | 1 | 0.9 | 18 | 1 | 5.6 | 0.1 | 500 | 0.1 | 0.1 | - |
| 1,2,4-Trichlorobenzene | 124 | 3 | 2.4 | 19 | 3 | 15.8 | 0.1 | 500 | 0.4 | 2.2 | 70 |
| 1,1,1-Trichloroethane | 139 | 3 | 2.1 | 19 | 3 | 15.8 | 0.09 | 500 | 0.6 | 22 | 200 |
| Trichloroethene | 108 | 25 | 18.8 | 19 | 6 | 31.6 | 0.1 | 500 | 0.5 | 700 | 5 |
| Vinyl Chloride | 78 | 54 | 40.9 | 19 | 9 | 47.4 | 0.2 | 5000 | 1.7 | 530 | 2 |
| Xylenes | NA[e/] | NA | NA | 0 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 71 | 18 | 20.2 | 18 | 7 | 38.9 | 0.2 | 500 | 0.28 | 74.8 | 750 |
| Ortho-Xylene | 73 | 20 | 21.5 | 18 | 8 | 44.4 | 0.1 | 500 | 0.1 | 47 | 600 |

## TABLE 2.1 (Continued)
## CONSTITUENTS OF POTENTIAL CONCERN DETECTED IN GROUNDWATER
### REMEDIAL PROCESS OPTIMIZATION, OU1
### HILL AIR FORCE BASE, UTAH

### Monitoring Zone A2

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 114 | 4 | 3.4 | 15 | 3 | 20.0 | 0.1 | 50 | 0.1 | 580 | 5 |
| Toluene | 2 | 5 | 71.4 | 7 | 5 | 71.4 | 0.2 | 0.2 | 0.3 | 2.2 | 1,000 |
| Chlorobenzene | 7 | 5 | 41.7 | 12 | 5 | 41.7 | 0.1 | 0.1 | 0.1 | 0.4 | 100 |
| 1,1-Dichloroethane | 85 | 28 | 24.8 | 15 | 5 | 33.3 | 0.08 | 50 | 0.4 | 130 | 790 |
| 1,2-Dichloroethane | 85 | 23 | 21.3 | 15 | 5 | 33.3 | 0.09 | 50 | 0.2 | 130 | 5 |
| cis-1,2-Dichloroethene | 55 | 26 | 32.1 | 14 | 6 | 42.9 | 0.1 | 25 | 0.18 | 2000 | 70 |
| trans-Dichloroethene | 66 | 14 | 17.5 | 14 | 3 | 21.4 | 0.1 | 25 | 0.3 | 1.8 | 100 |
| 1,2-Dichlorobenzene | 8 | 4 | 33.3 | 12 | 4 | 33.3 | 0.1 | 0.1 | 0.1 | 0.2 | 600 |
| 1,3-Dichlorobenzene | 111 | 3 | 2.6 | 15 | 2 | 13.3 | 0.1 | 25 | 0.9 | 2.7 | - |
| 1,4-Dichlorobenzene | 10 | 2 | 16.7 | 12 | 2 | 16.7 | 0.1 | 0.1 | 0.1 | 0.1 | 75 |
| 2,4-Dimethylphenol | 13 | 0 | 0.0 | 12 | 0 | 0.0 | 2.7 | 10 | ND[f/] | ND | 600 |
| Ethylbenzene | 121 | 0 | 0.0 | 15 | 0 | 0.0 | 0.1 | 50 | ND | ND | 700 |
| 4-Methylphenol | 12 | 0 | 0.0 | 12 | 0 | 0.0 | 5 | 10 | ND | ND | 1,500 |
| Tetrachloroethene | 31 | 1 | 3.1 | 21 | 1 | 4.8 | 0.03 | 5 | 0.4 | 0.4 | 5 |
| 1,2,3-Trichlorobenzene | 84 | 0 | 0.0 | 14 | 0 | 0.0 | 0.1 | 25 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 99 | 0 | 0.0 | 15 | 0 | 0.0 | 0.1 | 25 | ND | ND | 70 |
| 1,1,1-Trichloroethane | 104 | 11 | 9.6 | 15 | 3 | 20.0 | 0.09 | 50 | 0.7 | 230 | 200 |
| Trichloroethene | 92 | 20 | 17.9 | 15 | 8 | 53.3 | 0.1 | 50 | 0.1 | 310 | 5 |
| Vinyl Chloride | 93 | 14 | 13.1 | 15 | 4 | 26.7 | 0.1 | 25 | 0.2 | 370 | 2 |
| Xylenes | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 12 | 0 | 0.0 | 12 | 0 | 0.0 | 0.2 | 0.5 | ND | ND | 750 |
| Ortho-Xylene | 12 | 0 | 0.0 | 12 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 600 |

### Monitoring Zone A3

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 64 | 0 | 0.0 | 8 | 0 | 0.0 | 0.1 | 50 | ND | ND | 5 |
| Toluene | 5 | 1 | 16.7 | 6 | 1 | 16.7 | 0.1 | 0.2 | 0.2 | 0.2 | 1,000 |
| Chlorobenzene | 7 | 0 | 0.0 | 7 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 100 |
| 1,1-Dichloroethane | 36 | 16 | 30.8 | 8 | 4 | 50.0 | 0.1 | 50 | 3.3 | 14 | 790 |
| 1,2-Dichloroethane | 57 | 7 | 10.9 | 8 | 4 | 50.0 | 0.1 | 50 | 0.6 | 5 | 5 |
| cis-1,2-Dichloroethene | 11 | 44 | 80.0 | 8 | 5 | 62.5 | 0.1 | 200 | 3.9 | 1090 | 70 |
| trans-Dichloroethene | 44 | 14 | 24.1 | 8 | 4 | 50.0 | 0.1 | 25 | 0.8 | 110 | 100 |
| 1,2-Dichlorobenzene | 7 | 0 | 0.0 | 7 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 600 |
| 1,3-Dichlorobenzene | 60 | 0 | 0.0 | 8 | 0 | 0.0 | 0.1 | 25 | ND | ND | - |
| 1,4-Dichlorobenzene | 7 | 0 | 0.0 | 7 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 75 |
| 2,4-Dimethylphenol | 2 | 0 | 0.0 | 2 | 0 | 0.0 | 2.7 | 2.7 | ND | ND | 600 |
| Ethylbenzene | 64 | 0 | 0.0 | 8 | 0 | 0.0 | 0.1 | 50 | ND | ND | 700 |
| 4-Methylphenol | 2 | 0 | 0.0 | 2 | 0 | 0.0 | 5 | 5 | ND | ND | 1,500 |
| Tetrachloroethene | 15 | 0 | 0.0 | 8 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| 1,2,3-Trichlorobenzene | 58 | 0 | 0.0 | 8 | 0 | 0.0 | 0.1 | 25 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 60 | 0 | 0.0 | 8 | 0 | 0.0 | 0.1 | 25 | ND | ND | 70 |
| 1,1,1-Trichloroethane | 55 | 6 | 9.8 | 8 | 2 | 25.0 | 0.1 | 50 | 3 | 6.8 | 200 |
| Trichloroethene | 17 | 42 | 71.2 | 7 | 5 | 71.4 | 0.1 | 50 | 1.8 | 40 | 5 |
| Vinyl Chloride | 52 | 9 | 14.8 | 8 | 4 | 50.0 | 0.1 | 25 | 0.2 | 12 | 2 |
| Xylenes | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 7 | 0 | 0.0 | 7 | 0 | 0.0 | 0.2 | 0.5 | ND | ND | 750 |
| Ortho-Xylene | 7 | 0 | 0.0 | 7 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 600 |

**TABLE 2.1 (Continued)**
**CONSTITUENTS OF POTENTIAL CONCERN DETECTED IN GROUNDWATER**
**REMEDIAL PROCESS OPTIMIZATION, OU1**
**HILL AIR FORCE BASE, UTAH**

**Monitoring Zone T1**

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 113 | 0 | 0.0 | 21 | 0 | 0.0 | 0.1 | 25 | ND | ND | 5 |
| Toluene | 11 | 0 | 0.0 | 11 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 1,000 |
| Chlorobenzene | 11 | 0 | 0.0 | 11 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 100 |
| 1,1-Dichloroethane | 43 | 49 | 53.3 | 21 | 14 | 66.7 | 0.1 | 25 | 0.63 | 28 | 790 |
| 1,2-Dichloroethane | 111 | 2 | 1.8 | 21 | 2 | 9.5 | 0.1 | 25 | 0.3 | 0.3 | 5 |
| cis-1,2-Dichloroethene | 11 | 83 | 88.3 | 20 | 15 | 75.0 | 0.1 | 50 | 0.2 | 910 | 70 |
| trans-Dichloroethene | 3 | 8 | 72.7 | 11 | 8 | 72.7 | 0.1 | 0.2 | 0.3 | 13.3 | 100 |
| 1,2-Dichlorobenzene | 11 | 0 | 0.0 | 11 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 600 |
| 1,3-Dichlorobenzene | 106 | 0 | 0.0 | 21 | 0 | 0.0 | 0.1 | 20 | ND | ND | - |
| 1,4-Dichlorobenzene | 11 | 0 | 0.0 | 11 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 75 |
| 2,4-Dimethylphenol | 8 | 0 | 0.0 | 8 | 0 | 0.0 | 2.7 | 2.7 | ND | ND | 600 |
| Ethylbenzene | 114 | 0 | 0.0 | 21 | 0 | 0.0 | 0.1 | 25 | ND | ND | 700 |
| 4-Methylphenol | 8 | 0 | 0.0 | 8 | 0 | 0.0 | 5 | 5 | ND | ND | 1,500 |
| Tetrachloroethene | 34 | 0 | 0.0 | 24 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| 1,2,3-Trichlorobenzene | 100 | 0 | 0.0 | 21 | 0 | 0.0 | 0.1 | 20 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 106 | 0 | 0.0 | 21 | 0 | 0.0 | 0.1 | 20 | ND | ND | 70 |
| 1,1,1-Trichloroethane | 77 | 10 | 11.5 | 21 | 5 | 23.8 | 0.1 | 25 | 0.2 | 14 | 200 |
| Trichloroethene | 46 | 53 | 53.5 | 20 | 11 | 55.0 | 0.1 | 20 | 0.2 | 22 | 5 |
| Vinyl Chloride | 9 | 2 | 18.2 | 11 | 2 | 18.2 | 0.1 | 0.2 | 0.2 | 0.2 | 2 |
| Xylenes | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 11 | 0 | 0.0 | 11 | 0 | 0.0 | 0.2 | 0.5 | ND | ND | 750 |
| Ortho-Xylene | 11 | 0 | 0.0 | 11 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 600 |

**Monitoring Zone A4**

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 78 | 1 | 1.3 | 16 | 1 | 6.3 | 0.1 | 5 | 2.2 | 2.2 | 5 |
| Toluene | 45 | 14 | 23.7 | 15 | 7 | 46.7 | 0.1 | 5 | 0.082 | 5.2 | 1,000 |
| Chlorobenzene | 10 | 0 | 0.0 | 10 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 100 |
| 1,1-Dichloroethane | 63 | 3 | 4.5 | 16 | 3 | 18.8 | 0.1 | 5 | 0.3 | 1.1 | 790 |
| 1,2-Dichloroethane | 79 | 0 | 0.0 | 16 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| cis-1,2-Dichloroethene | 23 | 33 | 58.9 | 15 | 9 | 60.0 | 0.1 | 5 | 0.13 | 59.1 | 70 |
| trans-Dichloroethene | 8 | 2 | 20.0 | 10 | 2 | 20.0 | 0.1 | 0.2 | 0.2 | 0.5 | 100 |
| 1,2-Dichlorobenzene | 10 | 0 | 0.0 | 10 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 600 |
| 1,3-Dichlorobenzene | 72 | 0 | 0.0 | 16 | 0 | 0.0 | 0.1 | 5 | ND | ND | - |
| 1,4-Dichlorobenzene | 10 | 0 | 0.0 | 10 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 75 |
| 2,4-Dimethylphenol | 5 | 0 | 0.0 | 5 | 0 | 0.0 | 2.7 | 10 | ND | ND | 600 |
| Ethylbenzene | 78 | 1 | 1.3 | 16 | 1 | 6.3 | 0.1 | 5 | 0.5 | 0.5 | 700 |
| 4-Methylphenol | 5 | 0 | 0.0 | 5 | 0 | 0.0 | 5 | 10 | ND | ND | 1,500 |
| Tetrachloroethene | 26 | 0 | 0.0 | 16 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| 1,2,3-Trichlorobenzene | 66 | 0 | 0.0 | 16 | 0 | 0.0 | 0.1 | 5 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 71 | 0 | 0.0 | 16 | 0 | 0.0 | 0.1 | 5 | ND | ND | 70 |
| 1,1,1-Trichloroethane | 79 | 0 | 0.0 | 16 | 0 | 0.0 | 0.1 | 5 | ND | ND | 200 |
| Trichloroethene | 39 | 19 | 32.8 | 15 | 7 | 46.7 | 0.1 | 5 | 0.27 | 30 | 5 |
| Vinyl Chloride | 8 | 2 | 20.0 | 10 | 2 | 20.0 | 0.1 | 0.2 | 0.2 | 0.6 | 2 |
| Xylenes | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 9 | 1 | 10.0 | 10 | 1 | 10.0 | 0.2 | 0.5 | 1.8 | 1.8 | 750 |
| Ortho-Xylene | 9 | 1 | 10.0 | 10 | 1 | 10.0 | 0.1 | 0.2 | 0.8 | 0.8 | 600 |

**TABLE 2.1 (Continued)**
**CONSTITUENTS OF POTENTIAL CONCERN DETECTED IN GROUNDWATER**
**REMEDIAL PROCESS OPTIMIZATION, OU1**
**HILL AIR FORCE BASE, UTAH**

**Monitoring Zone A5**

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 1 | ND | ND | 5 |
| Toluene | 10 | 5 | 33.3 | 4 | 1 | 25.0 | 0.1 | 5 | 0.23 | 3.5 | 1,000 |
| Chlorobenzene | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 100 |
| 1,1-Dichloroethane | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | 790 |
| 1,2-Dichloroethane | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| cis-1,2-Dichloroethene | 6 | 9 | 60.0 | 4 | 3 | 75.0 | 0.1 | 5 | 0.19 | 21 | 70 |
| trans-Dichloroethene | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 100 |
| 1,2-Dichlorobenzene | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 600 |
| 1,3-Dichlorobenzene | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | - |
| 1,4-Dichlorobenzene | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 75 |
| 2,4-Dimethylphenol | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 600 |
| Ethylbenzene | 16 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | 700 |
| 4-Methylphenol | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 1,500 |
| Tetrachloroethene | 8 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| 1,2,3-Trichlorobenzene | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | 70 |
| 1,1,1-Trichloroethane | 18 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 5 | ND | ND | 200 |
| Trichloroethene | 2 | 2 | 50.0 | 4 | 2 | 50.0 | 0.1 | 0.2 | 0.1 | 0.4 | 5 |
| Vinyl Chloride | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 2 |
| Xylenes | NA | NA | 0.0 | 0 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.2 | 0.5 | ND | ND | 750 |
| Ortho-Xylene | 4 | 0 | 0.0 | 4 | 0 | 0.0 | 0.1 | 0.2 | ND | ND | 600 |

**Monitoring Zone A6**

| Chemical | Detection Frequency Non-Detects | Detection Frequency Detects | Percent Detects | Number of Wells Sampled | Number of Wells with Detects | Percentage of Wells with Detects | Detection Limits (µg/L) Minimum | Detection Limits (µg/L) Maximum | Detected Concentrations (µg/L) Minimum | Detected Concentrations (µg/L) Maximum | PRG (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 1 | ND | ND | 5 |
| Toluene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 1,000 |
| Chlorobenzene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 100 |
| 1,1-Dichloroethane | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | 790 |
| 1,2-Dichloroethane | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| cis-1,2-Dichloroethene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 70 |
| trans-Dichloroethene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 100 |
| 1,2-Dichlorobenzene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 600 |
| 1,3-Dichlorobenzene | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | - |
| 1,4-Dichlorobenzene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 75 |
| 2,4-Dimethylphenol | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 10 | 10 | ND | ND | 600 |
| Ethylbenzene | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | 700 |
| 4-Methylphenol | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 10 | 10 | ND | ND | 1,500 |
| Tetrachloroethene | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | 5 |
| 1,2,3-Trichlorobenzene | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | 70 |
| 1,1,1-Trichloroethane | 2 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 5 | ND | ND | 200 |
| Trichloroethene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 5 |
| Vinyl Chloride | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 2 |
| Xylenes | NA | NA | 0.0 | 1 | 0 | 0.0 | NA | NA | NA | NA | 10,000 |
| Meta- and Para- Xylene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.2 | 0.2 | ND | ND | 750 |
| Ortho-Xylene | 1 | 0 | 0.0 | 1 | 0 | 0.0 | 0.1 | 0.1 | ND | ND | 600 |

**TABLE 2.1 (Continued)**
**CONSTITUENTS OF POTENTIAL CONCERN DETECTED IN GROUNDWATER**
**REMEDIAL PROCESS OPTIMIZATION, OU1**
**HILL AIR FORCE BASE, UTAH**

| Springs and Seeps | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Detection Frequency | | Percent | Number of | Number of Springs | Percentage of | Detection Limits (µg/L) | | Detected Concentrations (µg/L) | | PRG |
| Chemical | Non-Detects | Detects | Detects | Springs Sampled | with Detects | Springs with Detects | Minimum | Maximum | Minimum | Maximum | (µg/L) |
| Benzene | 200 | 33 | 14.2 | 52 | 4 | 7.7 | 0.1 | 25 | 0.16 | 7.3 | 5 |
| Toluene | 192 | 18 | 8.6 | 51 | 6 | 11.8 | 0.2 | 25 | 0.074 | 34 | 1,000 |
| Chlorobenzene | 217 | 15 | 6.5 | 52 | 3 | 5.8 | 0.1 | 25 | 0.089 | 2.2 | 100 |
| 1,1-Dichloroethane | 136 | 96 | 41.4 | 52 | 12 | 23.1 | 0.1 | 25 | 0.11 | 9.8 | 790 |
| 1,2-Dichloroethane | 196 | 37 | 15.9 | 52 | 10 | 19.2 | 0.3 | 25 | 0.17 | 1.5 | 5 |
| cis-1,2-Dichloroethene | 95 | 106 | 52.7 | 51 | 18 | 35.3 | 0.2 | 50 | 0.14 | 526 | 70 |
| trans-Dichloroethene | 192 | 11 | 5.4 | 51 | 5 | 9.8 | 0.2 | 12 | 0.16 | 2.2 | 100 |
| 1,2-Dichlorobenzene | 183 | 31 | 14.5 | 51 | 4 | 7.8 | 0.1 | 12 | 0.13 | 1.9 | 600 |
| 1,3-Dichlorobenzene | 210 | 4 | 1.9 | 51 | 2 | 3.9 | 0.3 | 12 | 0.1 | 0.27 | - |
| 1,4-Dichlorobenzene | 172 | 40 | 18.9 | 51 | 5 | 9.8 | 0.1 | 12 | 0.11 | 14 | 75 |
| 2,4-Dimethylphenol | 17 | 0 | 0.0 | 6 | 0 | 0.0 | 1.8 | 10 | ND | ND | 600 |
| Ethylbenzene | 215 | 18 | 7.7 | 52 | 4 | 7.7 | 0.3 | 25 | 0.095 | 34 | 700 |
| 4-Methylphenol | 17 | 0 | 0.0 | 6 | 0 | 0.0 | 1.8 | 10 | ND | ND | 1,500 |
| Tetrachloroethene | 213 | 8 | 3.6 | 52 | 7 | 13.5 | 0.3 | 25 | 0.19 | 6.2 | 5 |
| 1,2,3-Trichlorobenzene | 197 | 0 | 0.0 | 51 | 0 | 0.0 | 0.1 | 12 | ND | ND | - |
| 1,2,4-Trichlorobenzene | 207 | 4 | 1.9 | 51 | 4 | 7.8 | 0.1 | 12 | 0.11 | 0.16 | 70 |
| 1,1,1-Trichloroethane | 225 | 8 | 3.4 | 52 | 2 | 3.9 | 0.2 | 25 | 0.29 | 29 | 200 |
| Trichloroethene | 184 | 46 | 20.0 | 52 | 9 | 17.3 | 0.2 | 25 | 0.15 | 23 | 5 |
| Vinyl Chloride | 186 | 47 | 20.2 | 52 | 4 | 7.7 | 0.2 | 12 | 0.35 | 54.1 | 2 |
| Xylenes | 61 | 3 | 4.7 | 41 | 3 | 5.8 | 1 | 25 | 0.34 | 2.7 | 10,000 |
| Meta- and Para- Xylene | 159 | 11 | 6.5 | 38 | 6 | 14.6 | 0.5 | 12 | 0.22 | 26 | 750 |
| Ortho-Xylene | 156 | 14 | 8.2 | 38 | 6 | 15.8 | 0.2 | 12 | 0.084 | 17 | 600 |

[a/] µg/L = micrograms per liter.
[b/] PRG = Preliminary Remediation Goal.
[c/] Shading indicates that the maximum detected concentration exceeded the PRG.
[d/] "-" indicates no PRG or Maximum Contaminant Level has been established for this chemical.
[e/] NA = Not applicable.
[f/] ND = Not detected.

Most of the groundwater contaminants in this area probably originated at the CDPs and FTA 1. Sources of petroleum fuel contamination may also be present in the eastern part of Landfill 3.

#### 2.3.3.2 Alpine Formation (A1) Groundwater

The principal contaminants that have been detected in groundwater of the A1 water-bearing zone are chlorinated solvents and petroleum fuel constituents (Table 2.1), similar to the contaminants that have been detected in the overlying S1 water-bearing zone, although contaminant concentrations in groundwater of the A1 zone are generally lower than concentrations in groundwater of the S1 zone. Contaminants in groundwater of the A1 zone appear to have migrated from the overlying S1 water-bearing zone. The areal extent of contaminants in groundwater of the A1 water-bearing zone is approximately the same as the overlying S1 zone, but contaminants in the A1 zone have migrated further to the north than the contaminants in groundwater of the S1 water-bearing zone. This is most probably a result of the general northerly direction of groundwater movement in the A1 water-bearing zone.

DCE and vinyl chloride, at concentrations ranging to 5,000 μg/L and 530 μg/L, respectively, are the most widespread contaminants; and the areal extent of DCE and vinyl chloride in groundwater of the A1 zone is generally similar. TCE also has been detected, at concentrations up to 700 μg/L; and several other contaminants have been detected, at concentrations that exceed their respective MCLs. The highest concentrations of benzene, toluene, and xylene compounds are associated with the LNAPL plumes emanating from the CDPs and FTA 1.

#### 2.3.3.3 Alpine Formation (A2) Groundwater

The principal contaminants that have been detected in groundwater of the A2 water-bearing zone are chlorinated solvents and petroleum fuel constituents (Table 2.1), similar to the contaminants that have been detected in overlying water-bearing zones, although the concentrations of contaminants in groundwater of the A2 zone are at trace levels. As with groundwater in the S1 and A1 water-bearing zones, DCE is the most widespread contaminant in the A2 zone. Contaminants in groundwater of the A2 zone appear to have migrated from the overlying A1 and S1 water-bearing zones. After contaminants were introduced to the A2 water-bearing zone, most contaminant migration in the A2 zone appears to have occurred in buried channels, since most contaminant mass in groundwater at off-Base locations has been detected in probable buried channels.

DCE is the most widespread contaminant detected in groundwater of the A2 zone, with concentrations ranging to 2,000 μg/L. TCE has been detected at concentrations ranging to 310 μg/L; and benzene, 1,2-dichloroethane (1,2-DCA), cis-1,2-DCE, 1,1,1-trichloroethane (1,1,1-TCA), TCE, and vinyl chloride have been detected at concentrations that exceeded the respective MCLs for these compounds (Table 2.1). Several other chlorinated aromatic compounds were detected at trace concentrations. SVOCs were not detected.

### 2.3.3.4 Alpine Formation (A3/T1) Groundwater

The principal contaminants that have been detected in groundwater of the A3/T1 water-bearing zone are chlorinated solvents, although the concentrations of contaminants in groundwater of the A3/T1 zone are at much lower than concentrations that have been detected in overlying water-bearing zones (Table 2.1). Several other compounds have been detected at trace concentrations; the suite of detected compounds is similar to those detected in the S1, A1, and A2 water-bearing zones, indicating that contaminants have migrated to the A3/T1 zone from groundwater in overlying units.

DCE is the most widespread contaminant in groundwater of the A3/T1 zone, and has been detected at concentrations ranging to 1,090 μg/L (Table 2.1). In most parts of the A3/T1 water-bearing zone, DCE is the only contaminant that has been detected; however, trans 1,2-dichloroethene (trans-1,2-DCE), TCE, and vinyl chloride have also been detected at concentrations that exceed the respective MCLs for these compounds. These contaminants were detected in association with higher concentrations of DCE. Several other chlorinated aromatic compounds have been detected at trace concentrations. SVOCs were not detected in groundwater of the A3/T1 zone.

### 3.3.3.5 Alpine Formation (A4, A5, and A6) Groundwater

Volatile organic compounds (VOCs) have been detected in groundwater in the A4 and A5 water-bearing zones, but have not been detected in groundwater of the A6 water-bearing zone (Table 2.1). The principal contaminants found in the A4 and A5 water-bearing zones are chlorinated solvents, similar to those detected within the A3/T1 water-bearing zone, but at significantly lower concentrations. This indicates that contaminants have migrated to the A4 and A5 zones from groundwater in overlying units.

DCE is the most widespread contaminant in groundwater of the A4 water-bearing zone, and is the only contaminant of concern that has been detected in groundwater of the A5 zone (Table 2.1). SVOCs have not been detected in either water-bearing zone.

### 2.3.3.6 Delta Aquifer

Groundwater samples from monitoring well U1-197, completed in the deep groundwater aquifer, were analyzed for VOCs and SVOCs. No volatile or semi-volatile compounds were detected in samples from the groundwater aquifer.

### 2.3.3.7 Springs and Seeps

A total of 19 springs and seeps have been identified in the on-Base and off-Base portions of OU1 (Montgomery Watson, 1995a). As shown in Table 2.1, VOCs detected in samples from the springs and seeps at concentrations above PRGs include benzene, cis-1,2-DCE, PCE, TCE, and vinyl chloride. Consideration of the springs and seeps at OU1 is necessary, because they represent discharge points for some of the groundwater that originates at Hill AFB, and has moved off the bluff and over the edge of the escarpment bordering OU1.

#### 2.3.3.8 Summary of Groundwater and Spring Water at OU1

The nature and distribution of VOCs in groundwater of the Provo Formation at OU1 indicate that VOCs, probably originating at the CDPs and FTA 1, migrated from those source areas to the uppermost water-bearing zone in the shallow subsurface (zone S1) beneath Hill AFB OU1 (Montgomery Watson, 1995a). Although hydraulic communication among the various water-bearing zones is limited, and probably occurs only locally, the similarity of VOCs detected in groundwater of the S1 zone and in water-bearing zones A1, A2, A3/T1, A4, and A5 (which are stratigraphically below the S1 zone), indicates that contaminants have migrated from the S1 zone into deeper water-bearing units, and have moved via preferential migration pathways over the edge of the escarpment and into the T1 groundwater system of the Weber River Valley. Some contaminants have also been detected in water from particular surface springs and seeps, indicating that these springs/seeps are discharge points for contaminated groundwater, originating at OU1. Because the various water-bearing zones in the groundwater system are in hydraulic communication to only a limited degree, the concentrations of contaminants decline rapidly with increasing depth below the S1 zone, and with increasing migration distance downgradient from source areas.

## 2.4 REGULATORY FRAMEWORK

Hill AFB and OU1 were originally placed on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priorities List (NPL) in July 1987. A Federal Facilities Agreement (FFA) among Hill AFB, the United States Environmental Protection Agency (USEPA), and the Utah Department of Health (now the Utah Department of Environmental Quality [UDEQ]) was signed in April 1991. The purpose of the agreement was to establish a framework and schedule for developing, implementing, and monitoring appropriate remedial actions at Hill AFB in accordance with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP). The FFA also guides the remedial design/remedial action (RD/RA) process.

In September 1998, the USEPA, UDEQ, and the US Air Force signed a ROD. The ROD (EMD, 1998) presents the selected remedies for OU1 at Hill AFB. The remedies were selected in accordance with the requirements of CERCLA, as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, and the NCP. The intent of the remedial actions specified in the ROD is to achieve appropriate remediation goals (also specified in the ROD). Preliminary remediation goals (PRGs) establish OU1 media-specific concentrations of contaminants of concern that will pose no unacceptable risks to human health or the environment. The PRGs for soil and groundwater are provided in Table 7.1 and 7.2 of the ROD. Considerations used in setting remediation goals for OU1 soil, groundwater, surface water, LNAPL, and landfill contents and gas are:

- PRGs representing concentration levels corresponding to an excess cancer risk between $1 \times 10^{-4}$ and $1 \times 10^{-6}$, a chronic health risk defined by a hazard quotient of 1, and/or a significant ecological risk. PRGs were presented in the ROD at the $1 \times 10^{-6}$ level, because the PRG serves as "the point of departure," as required by the NCP.

- Chemical-specific Applicable or Relevant and Appropriate Requirements (ARARs), which include MCLs and non-zero maximum contaminant level goals for potential sources of drinking water.

Applicable requirements are those cleanup standards, standards for control, and substantive requirements, criteria, or limitations promulgated under federal or State law that specifically address a hazardous substance, pollutant, contaminant, remedial action, or location at a CERCLA site. Potential ARARs identified for OU1 are provided in Appendix A of the ROD (EMD, 1998).

## 2.5 REMEDIATION SYSTEM DESCRIPTION

### 2.5.1 Site Remediation History

Remediation systems were initially constructed at OU1 in response to a Cease and Desist Order for leachate discharging below Landfill 4. The order was issued by the Utah Water Pollution Control Board (currently the State of Utah Division of Water Quality) on July 23, 1984. The leachate was detected at Springs U1-303 and U1-304 (Figure 2.6). Hill AFB implemented the interim remedial measures to prevent exposure to contamination associated with the OU1 site and to limit the mobility of contaminants at OU1. These actions were implemented prior to the promulgation of SARA regulations, and some of the actions were taken without EPA and UDEQ oversight. The following remedial measures were implemented by Hill AFB as interim measures to address the requirements of the Cease and Desist Order:

- Installation of low-permeability caps over source areas, in 1985 and 1986. These were designed to reduce infiltration of precipitation to the subsurface, thereby reducing the volume of groundwater movement through, and leachate generation from, source areas.

- Installation of a subsurface physical barrier in 1985 (soil/bentonite slurry cut-off wall), upgradient of the source areas. This was designed to reduce groundwater movement through the source areas.

- Collection and treatment of contaminated surface water (spring collection system), from off-Base springs located downgradient of the source areas in 1985.

- Extraction and treatment of contaminated groundwater (groundwater extraction trench) in the on-Base source area in 1985.

- Initiation of a groundwater and surface water monitoring program in 1990.

- Installation of a surface water seep collection system at Spring U1-307 in 1995.

### 2.5.2 Proposed Remedial Measures

Remedial actions proposed in the current ROD (EMD, 1998) for OU1 include measures to address source area contamination and measures to address non-source areas. Measures proposed in the ROD for source areas include construction of additional dewatering trenches and repair of the existing landfill caps. The stated objective of source area remediation is to prevent the movement of contaminated groundwater and LNAPL from source areas to non-source areas, by dewatering the S1 zone in the Provo Formation, thereby also reducing the potential for movement of contaminated groundwater into the underlying Alpine Formation. Non-source area measures include upgrading the existing seep collection system, and remediation of contaminated groundwater by natural attenuation, supplemented by periodic monitoring of groundwater and surface-water conditions. The objective of non-source area remediation is to provide additional control over potential exposure to contaminants by preventing further releases of groundwater exceeding PRGs to land surface via seeps and springs, while relying on natural attenuation for groundwater restoration. Measures to be implemented jointly at source areas and the non-source area include institutional and engineering controls that will be enacted to prevent potentially unacceptable risks to human health and the environment.

The selected remedy described in the ROD for OU1 includes the following components:

**Source Area Measures**

- Dewater the source area Provo Formation (S1) water-bearing zone with extraction trenches;
- Recover LNAPL from the extraction trenches followed by proper disposal of the LNAPL;
- Treat groundwater derived from the extraction trenches at the OU2 air stripper treatment plant (ASTP), or the Hill AFB IWTP; and
- Repair and maintain the existing landfill caps and passive gas vent system.

**Non-Source Area Measures**

- Upgrade the spring collection system and treat collected surface water at the OU2 ASTP, at a new remote treatment plant, or at the IWTP;
- Excavate arsenic-contaminated spring sediments. The excavated sediments will be properly disposed at an approved, off-Base facility; and
- Conduct monitored natural attenuation of contaminants in groundwater of the Non-Source Area. This component of the selected remedy depends on intercepting contaminants moving in groundwater from the source area. Other remedies will be implemented if contaminant concentrations are not reduced to acceptable levels within a reasonable time frame.

**Source and Non-Source Area Joint Measures**

- Conduct periodic monitoring of environmental conditions;
- Implement institutional and engineering controls to prevent or mitigate potentially unacceptable risks to human health and the environment; and

- Designate a Corrective Action Management Unit (CAMU) to facilitate remedial actions. The existing contiguous area of contamination, comprising the source areas and non-source area will be designated as the CAMU.

The selected remedy for OU1 incorporates and expands upon prior response actions in order to address the principal threats posed by existing conditions at OU1, by minimizing or preventing direct contact with contaminated soils and landfill materials; preventing ingestion of and direct contact with contaminated groundwater, surface water, and sediments; and reducing or preventing continued off-Base migration of contaminants. Additional details of the proposed remedy are provided in the ROD (EMD, 1998) and the Draft PSVP (CH2M Hill, 1999a).

# SECTION 3

# RPO EVALUATION OF HILL AFB OU1

The remedies identified in the ROD (EMD, 1998) for Hill AFB OU1 have not yet been fully implemented; therefore, this RPO effort does not include evaluation and optimization of the remediation systems. The activities completed for the OU1 RPO evaluation included reviewing the PSVP and providing recommendations for its refinement, reviewing the MAROS tool as a beta test site and providing recommendations for its improvement, and providing comments to the LTMP based on data analysis utilizing the MAROS tool. These activities were not dependent on full implementation of the selected remedies, but rather were intended to guide decisions regarding future monitoring programs at Hill AFB OU1. This section discusses the approach that was used to evaluate the PSVP, MAROS, and the LTMP. Recommendations for modifications to the PSVP, the MAROS tool, and the LTMP are summarized in Section 4.

## 3.1 PERFORMANCE STANDARD VERIFICATION PLAN

The Draft PSVP for Hill AFB (CH2M Hill, 1999a) is currently being revised by the Base and its environmental contractor, CH2M Hill. This evaluation pertains to the Draft PSVP that was issued for internal review in June 1999. The PSVP is designed to "*document the procedures, methods of analysis, and monitoring plans that will be used to evaluate the performance, effectiveness, efficiency, and associated progress toward achievement of OU1 remediation goals and the ultimate closure of the site*" (CH2M Hill, 1999a, Section 1.1). As such, the PSVP "*is considered to be part of the OU1 remedial design*" (CH2M Hill, 1999a, Section 1.2), and ultimately will be subject to regulatory review and approval. The Draft PSVP identifies data quality objectives (DQOs), establishes monitoring criteria, recommends a monitoring network, and specifies procedures and schedules for each aspect of the remedies to be implemented at OU1.

The Draft PSVP states that monitoring results will be compared periodically with DQOs to assess the progress of remedial actions as part of the performance evaluation. Sections 4 and 5 of the Draft PSVP were reviewed in detail to assess whether the procedures described in the Draft PSVP are capable of achieving the objectives of the monitoring program, and whether the planned monitoring program will achieve monitoring objectives in a cost-effective manner. The objectives of the monitoring program, as presented in the Draft PSVP, are to:

- Document changes in the concentrations and spatial distribution of groundwater contaminants;

- Document compliance with air and water discharge requirements;

- Assess the effectiveness and efficiency of the remedial systems in achieving remediation objectives for soil and groundwater;
- Document rates of mass removal and total mass removed;
- Determine the process parameters for optimum system performance; and
- Document concerns or problems regarding system operation and maintenance (O&M) that may affect long-term system reliability and operating costs.

Section 4.0 of the Draft PSVP (CH2M Hill, 1999a), entitled "*Performance Monitoring,*" presents a clear and comprehensive framework for defining remedial action-specific monitoring criteria for DQOs, and recommends criteria for monitoring that will be used to evaluate the effectiveness and efficiency of the OU1 remedial actions. This section also provides recommendations for the frequency of sample collection at each monitoring well, and identifies monitoring points that should be abandoned. A thorough discussion of the proposed monitoring network is developed for the groundwater extraction trenches, the low-permeability caps, the monitored natural attenuation remedy, and the spring-water collection and remediation system. A qualitative review of all monitoring points included in the LTMP is provided in Table 4.2 of the Draft PSVP, which also summarizes the rationale and frequency of sampling at particular locations, and recommended analytical methods for samples collected at each monitoring point. Monitoring locations proposed for abandonment are listed in Table 4.3 of the Draft PSVP, together with rationale for abandonment.

The methodology described in the Draft PSVP for identifying those monitoring points to be sampled or abandoned primarily considers the relative locations of monitoring points with respect to the remediation system or to the plume of dissolved contaminants. It is Parsons ES's opinion that the methodology used to identify wells for continued monitoring should be modified to include statistical analysis to identify those monitoring points that may contribute information of potential significance in achieving the DQOs or tracking remediation performance. Personnel at the Base have recognized this potential shortcoming of the Draft PSVP, and have taken steps to improve the revised PSVP by specifying general statistical procedures for selecting sampling points and determining optimum sampling frequency. Section 4.1 of this RPO report describes a methodology that could be used for statistical evaluation of the monitoring system, and provides suggested text for possible inclusion in the PSVP.

Section 5 of the Draft PSVP (CH2M Hill, 1999a), entitled "*Performance Evaluation*," describes the protocols that will be used to evaluate the performance of the OU1 remedial actions. This section also describes data reporting procedures. Table 5.1 in the Draft PSVP provides a comprehensive list of the success/failure criteria to be used in evaluating various aspects of the performance of the remediation systems. Decision-tree flowcharts that incorporate success/failure criteria, and actions recommended to occur as a consequence of particular decisions, are also provided in Section 5 of the Draft PSVP. Although evaluation of trends in contaminant concentrations is identified in the evaluation steps of the decision-trees, there is no discussion in the text regarding methodologies to evaluate trends. The PSVP should be modified to include specific procedures for this evaluation. It is possible that this deficiency has been addressed in the revised version of the PSVP. The MAROS software, discussed in Section 3.2.1 of this

RPO report, may be a useful tool for examining temporal trends in monitoring data in the context of performance evaluation.

## 3.2 MAROS AND STATISTICAL EVALUATION OF GROUNDWATER MONITORING DATA

Groundwater monitoring programs have two primary objectives (USEPA, 1993; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal evaluation*); and

2. Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial evaluation*).

The relative success of any remediation system and its components (including the monitoring network) must be judged based on its ability to achieve the stated objectives of the system. As part of the Draft PSVP (CH2M Hill, 1999a), Hill AFB provided a summary of criteria used to evaluate monitoring points (Table 4.1 of the Draft PSVP), together with a qualitative review of all monitoring points to be used in long-term monitoring of conditions at OU1 (Table 4.2 of the Draft PSVP). Hydraulic conditions at monitoring points (water levels, flow rates) are proposed to be evaluated continuously (using continuously-recording electronic devices), or quarterly. Monitoring points to be sampled are proposed for sampling at an annual or biennial frequency. Those monitoring points not retained in the Draft PSVP (CH2M Hill, 1999a) have been proposed for abandonment. Table 4.3 of the Draft PSVP summarizes existing monitoring locations proposed for abandonment, together with rationale for abandonment.

The qualitative evaluation of the monitoring network provided in the Draft PSVP is thorough, sufficiently detailed, and demonstrates a sound understanding of the objectives of the monitoring network. The following evaluation of the groundwater monitoring data is therefore focused on the temporal and spatial aspects of the monitoring objectives.

### 3.2.1 Statistical Evaluation of Monitoring Data Using the MAROS Tool

In conjunction with the RPO assessment of the groundwater monitoring network at Hill AFB OU1, Parsons ES conducted a preliminary evaluation ("beta test") of the MAROS software program, developed by GSI for AFCEE, using monitoring data from OU1 at Hill AFB. MAROS was used to perform temporal and spatial evaluations of the groundwater monitoring program at OU1. A compact disk (CD) containing the MAROS software and users manual is included in Appendix C. The following subsections summarize the groundwater analytical data used in this evaluation, describe the MAROS tool, and present the results of the MAROS analyses. More rigorous statistical evaluations of the groundwater monitoring data are also discussed.

#### 3.2.1.1 Summary of Analytical Data

The set of chemical data used in the statistical evaluation of the monitoring program was compiled from groundwater monitoring data that have been collected at OU1 during the period 1983 (for some chemicals) through June 2000. Sampling events typically have occurred as frequently as every three months (quarterly monitoring); however, not every well is sampled every quarter.

The analytes detected in groundwater consist primarily of chlorinated solvent constituents and benzene, toluene, ethylbenzene, and xylene isomers (BTEX compounds). The chemicals of concern (COCs) most frequently detected in groundwater samples from OU1 include TCE, DCE isomers, and vinyl chloride. Over the years, the analytical methods used to identify these compounds have changed, and the associated method detection limits have improved (i.e., recent method detection limits are lower than historic method detection limits). Generally, chemical analyses performed after 1990 have lower detection limits. For example, until 1990 analyses for TCE and vinyl chloride were performed using the EPA method E601 method. From 1990 to 1995, chemical analyses were performed using the more accurate SW8240 method; and since 1995, the SW8260 method has been used. As a further example, the cis-1,2-DCE, trans-1,2-DCE, and 1,1-DCE isomers of DCE have been analyzed separately only since 1993. Prior to 1993, commonly used analytical methods could not distinguish among the DCE isomers, and all isomers of dichloroethene were summed as "total DCE isomers."

Potentially more than 20 constituents may be COCs in groundwater at Hill AFB OU1 (Section 2.3.3; Table 2.1). Prior to initiating the spatial and temporal evaluation of the groundwater monitoring network, the complete set of historical chemical data for OU1 was examined to determine which COCs should be included in the evaluation. In the uppermost water-bearing zone (zone S1), 12 VOCs (benzene, toluene, chlorobenzene, 1,1-dichloroethane [1,1-DCA], 1,2-DCA, cis-1,2-DCE, 1,2-dichlorobenzene [1,2-DCB], 1,4-dichlorobenzene [1,4-DCB], 1,2,4-trichlorobenzene [1,2,4-TCB], 1,1,1-TCA, TCE, and vinyl chloride) have been detected in one or more monitoring wells at OU1 at concentrations that exceed PRGs, and at frequencies in excess of about 5 percent (Table 2.1). These 12 constituents therefore represent potential COCs in groundwater from zone S1 at OU1. Similarly, up to seven VOCs, primarily TCE, DCE isomers, and vinyl chloride, have been detected in each of monitoring zones A1, A2, A3/T1, A4, and A5 at OU1, at concentrations that exceed PRGs, and at frequencies in excess of about 5 percent (Table 2.1).

For the purposes of this evaluation, maximum detected concentrations were compared with the PRGs, to identify potential COCs. If the maximum detected concentration for a given chemical was greater than the PRG for that chemical, then in most cases that chemical was retained for evaluation using MAROS. Most chemicals having a maximum detected concentration below the PRG were removed from consideration. Secondary factors that were considered included the frequency of detection of each chemical, and the number of wells in which a particular chemical was detected. In a few cases, chemicals present at concentrations below PRGs were included in the MAROS evaluation because the chemicals were detected in a majority of the samples analyzed, or in a majority of wells. Ten COCs (benzene, chlorobenzene, 1,1-DCA, 1,2-DCA, cis-1,2-DCE, 1,2-DCB, 1,4- DCB, 1,2,4-TCB, TCE, and vinyl chloride) in OU1 groundwater were selected for MAROS evaluation.

### 3.2.1.2 Description of MAROS Tool

The MAROS software actually consists of a set of small programs (macros) that operate within an electronic database environment (MicroSoft™ Access97®) and perform certain mathematical or statistical functions using data that have been loaded into the database. MAROS makes extensive use of graphical user interfaces (GUIs), and is generally a user-friendly tool. MAROS appears to have been developed primarily to assist non-technical personnel (e.g., facility environmental managers) in the organization, preliminary evaluation, and presentation of monitoring data.

One of the most important purposes of a monitoring program is to confirm that the contaminant plume is behaving as predicted. If a groundwater remediation system is effective, then over the long term, groundwater monitoring data should demonstrate a clear and meaningful decreasing trend in concentrations at appropriate monitoring points. Temporal data (chemical concentrations measured at different points in time) can be examined visually, or with statistical tests, to evaluate plume stability. If removal of contaminant mass is occurring in the subsurface as a consequence of attenuation processes or operation of the remediation system, mass removal will be apparent as a decrease in contaminant concentrations through time at a particular sampling location, as a decrease in contaminant concentrations with increasing distance from source areas, or as a change in the suite of contaminants through time or with increasing migration distance.

Temporal chemical-concentration data can be evaluated by plotting contaminant concentrations through time for individual monitoring wells (Figure 3.1), or by plotting contaminant concentrations versus downgradient distance from the contaminant source for several wells along the groundwater flowpath, over several monitoring events. Plotting temporal concentration data is recommended for any analysis of plume stability (Wiedemeier and Haas, 1999); however, visual identification of trends in plotted data may be a subjective process, particularly (as is likely) if the concentration data do not have a uniform trend, but are variable through time (Figure 3.2).

The possibility of arriving at incorrect conclusions regarding plume stability on the basis of visual examination of temporal concentration data can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including regression analyses and the Mann-Kendall test for trends. The Mann-Kendall non-parametric test (Gibbons, 1994) is well suited for application to the evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a temporal trend is present in contaminant concentrations detected through time in samples from an individual well. If a trend is determined to be present, a non-parametric slope of the trend line (change per unit time) can also be estimated using the test procedure. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually (Figure 3.2). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends), in assessing the statistical significance of temporal concentration trends.

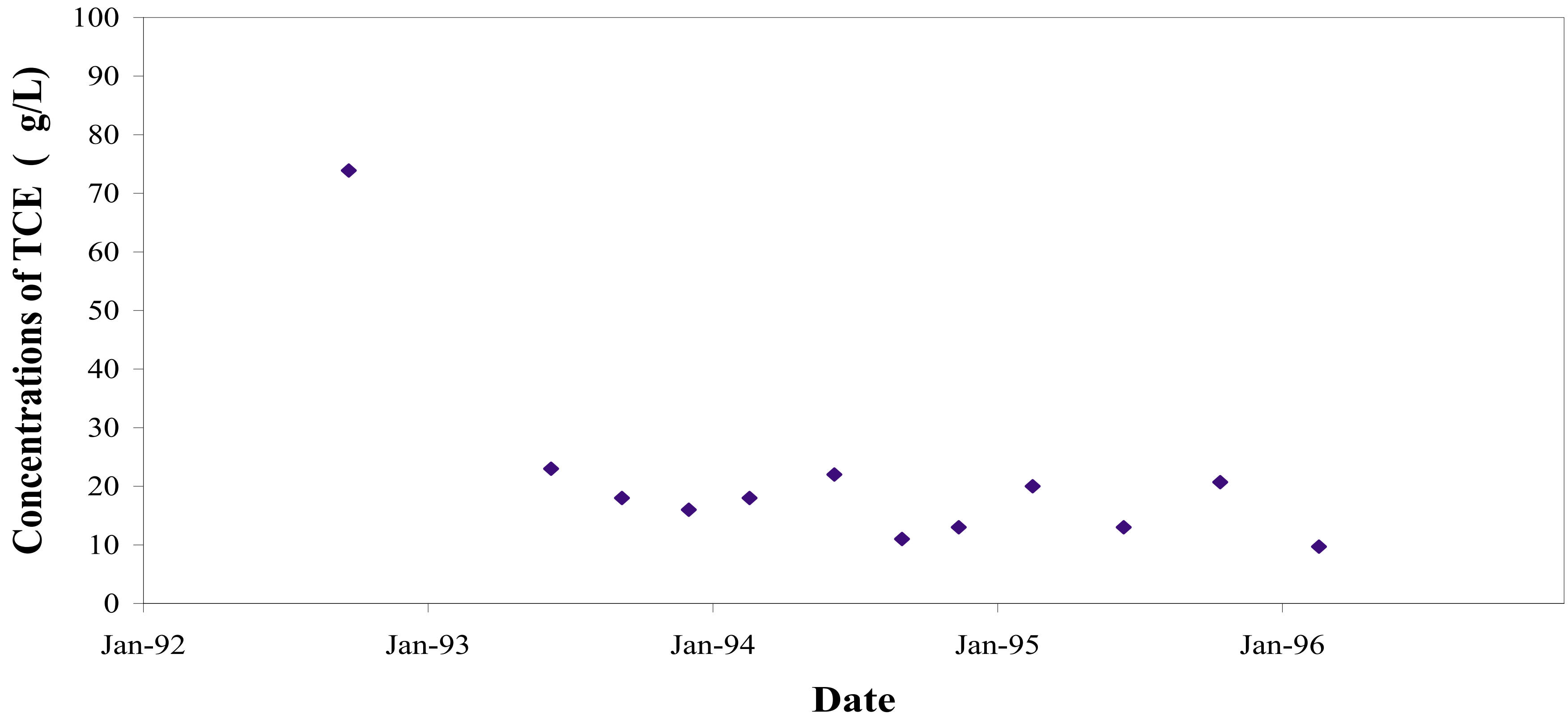


**FIGURE 3.1**

**TEMPORAL TREND IN TCE CONCENTRATIONS AT WELL U1-107**

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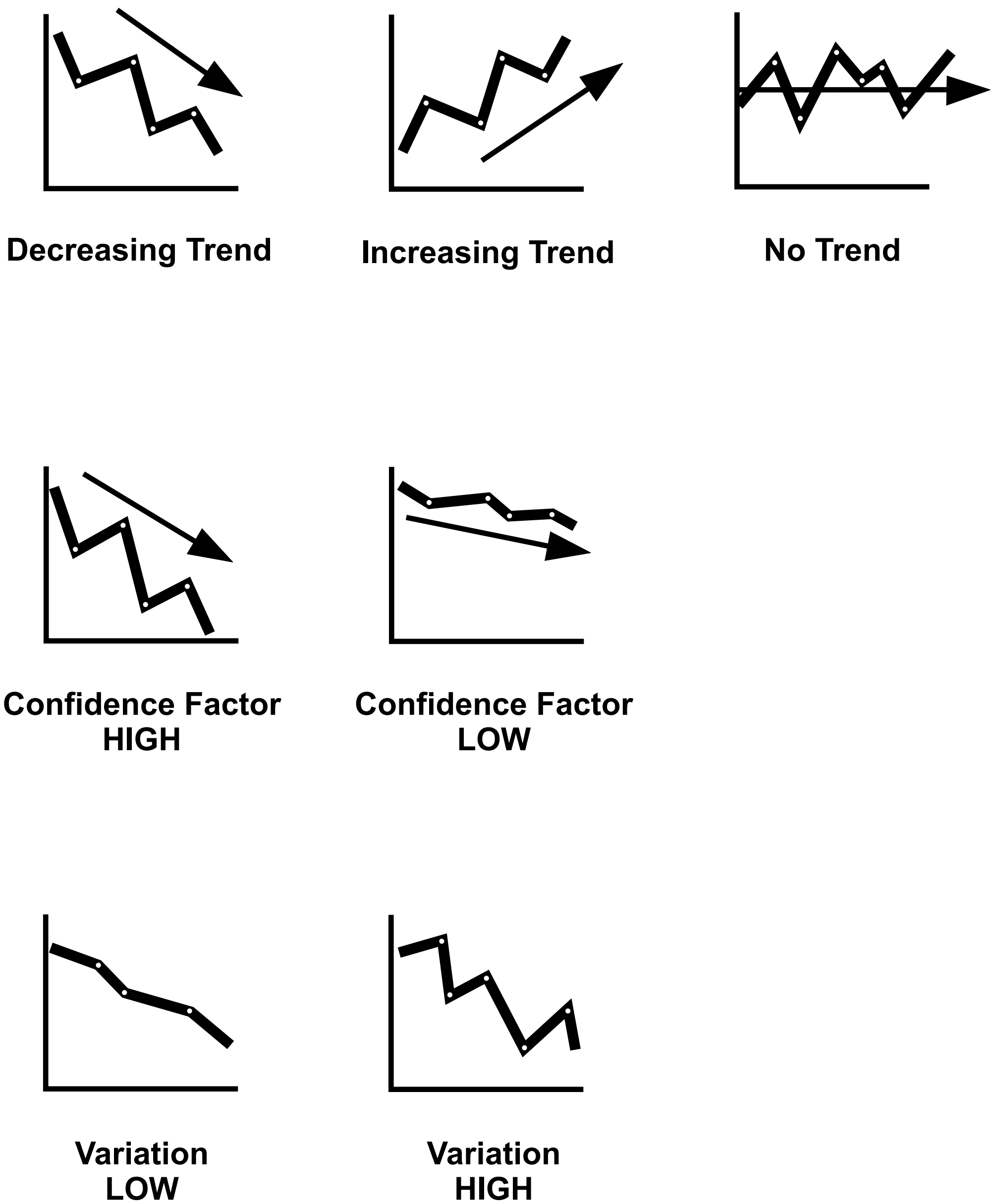


Source: Wiedemeier and Haas, 1999.

**FIGURE 3.2**

**CONCEPTUAL REPRESENTATION OF TEMPORAL TRENDS AND TEMPORAL VARIATION IN CONCENTRATIONS**

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Spatial statistical techniques can also be applied to the design and evaluation of monitoring programs to assess the relative value of data generated during monitoring, and to optimize monitoring networks. Although the MAROS tool is used to primarily evaluate temporal data, the tool also provides a simple spatial statistical method, based on a weighted "area-of-influence" approach (implemented using Delauney triangulation), for optimizing the locations of monitoring points. Formal decision trees, and user-defined secondary lines of evidence (empirical or modeling results) are also provided, and can be used to evaluate monitoring data and make recommendations for future sampling frequency, monitoring locations, and density of the monitoring network. Users can then apply the results of an evaluation, completed using the MAROS tool, to establish practical and cost-effective compliance monitoring goals for a specific site. MAROS can also be utilized to identify the COCs at the site; determine whether temporal trends in groundwater COC concentration data are statistically significant; evaluate the relative importance of each well in the monitoring network; and identify those wells that are statistically most relevant to the current sampling program. Application of the MAROS tool to the site-specific evaluation of a monitoring network is completely dependent upon the amount and quality of the available data (e.g., data requirements for a temporal trend analysis include a minimum of four distinct sampling events).

#### 3.2.1.3 MAROS Simulations

MAROS is designed to accept data in three formats: text files in Environmental Restoration Program Information Management System (ERPIMS) format, MicroSoft™ Access® ERPIMS files, and EXCEL® files. However, Parsons personnel experienced difficulties with importing EXCEL® files into the software. As a result, the data were re-formatted as ERPIMS Access® files and subsequently imported into MAROS.

Groundwater monitoring data have been collected from eight different water-bearing units (zones S1, A1, A2, A3, T1, A4, A5, and A6) in the subsurface beneath and downgradient of OU1. Consideration of the hydrologic characteristics of the groundwater system beneath OU1 indicates that hydraulic communication between the different water-bearing zones is probably limited; and the water-bearing zones probably function as separate units (Sections 2.2.5 and 2.3.3). Consequently, the monitoring results from each zone are considered to be distinct (in a statistical sense), and the groundwater monitoring data generated from each zone were examined separately from the groundwater monitoring data from other zones.

The S1 water-bearing zone of the Provo Formation (stratigraphically the uppermost water-bearing unit at Hill AFB OU1) is monitored by the greatest number of wells and has the most sample results available. Therefore, the monitoring results from the S1 water-bearing zone were included in the MAROS evaluation. After examining the available groundwater monitoring data, it was determined that relatively few monitoring wells completed in water-bearing zones A3, A5, and A6 had been regularly sampled. In addition, most of the COCs that were present in other zones were usually not detected in zones A3, A5, and A6; and those COCs that had been detected historically in these zones displayed a high percentage of non-detected values. Consequently, it was decided that the results from water-bearing zones A3, A5, and A6 would not be evaluated using the MAROS tool.

A limitation of the MAROS tool is that only five COCs can be examined in a single simulation. In order to evaluate all ten COCs identified (Section 3.2.1.1) in the S1 water-bearing zone, it was necessary to conduct two separate using five different COCs in each simulation (Table 3.1). In addition, because MAROS can only process monitoring data from 40 wells per simulation, the monitoring results from several wells were eliminated for the MAROS simulations. Wells were selected for elimination based on position relative to the plume, limited amount of sample results, or occurrence of mostly non-detects.

**TABLE 3.1**
**COCs EXAMINED USING MAROS TOOL**
**REMEDIAL PROCESS OPTIMIZATION. OU1**
**HILL AFB, UTAH**

| Zone S1(1) | Zone S1(2) | Zone A1 | Zone A2 | Zone T1 | Zone A4 |
|---|---|---|---|---|---|
| 1,1-DCA | 1,2-DCB | 1,2-DCB | 1,1,1-TCA | 1,1-DCA | TCE |
| 1,2-DCA | 1,4-DCB | 1,4-DCB | Benzene | Cis-1,2-DCE | |
| Benzene | 1,2,4-TCB | cis-1,2-DCE | Cis-1,2-DCE | TCE | |
| Chlorobenzene | TCE | TCE | TCE | Vinyl Chloride | |
| Cis-1,2-DCE | Vinyl Chloride | Vinyl Chloride | Vinyl Chloride | | |

The MAROS software uses site-specific hydrogeologic parameters, including groundwater seepage velocity, plume length, and distance from the plume to a downgradient receptor in the evaluation of the groundwater monitoring network. For the OU1 evaluation, these parameters (Table 3.2) were considered to be fixed regardless of the water-bearing zone being considered, and were identical for each simulation. The location and dimensions of the plume, and distances to the base boundary and potential receptors, were estimated by reviewing site maps (e.g., CH2M Hill, 1999a). The seepage velocity used in the simulations was an arithmetic average based on available groundwater velocities, ranging from $3.84 \times 10^{-7}$ to $1.45 \times 10^{-1}$ feet per second (ft/sec) at several different locations within OU1 (Montgomery Watson, 1995a). In addition, for the purpose of conducting the simulations, it was necessary to identify the relative location of each monitoring point within, or downgradient of the plume. Possible designations for the locations of monitoring points include "*source,*" "*tail,*" and "*not used.*" These designations were made for each monitoring point on the basis of visual inspection of plume maps for OU1 (CH2M Hill, 1999a), and consideration of the direction of groundwater movement in each water-bearing zone. The relative location assigned to each well can be found in the MAROS output results (Appendix A).

### 3.2.1.4 MAROS Simulation Results

Six separate simulations (described in Section 3.2.1.3) were completed using the MAROS tool, in order to examine the five selected water-bearing zones (zones S1 [two simulations], A1, A2, T1, and A4), and the COCs selected for each zone (Table 3.1). Sampling results generated during the most recent groundwater monitoring event at Hill AFB OU1 (June 2000) and historical groundwater monitoring data were included in the

**TABLE 3.2**
**SITE-SPECIFIC PARAMETERS USED IN MAROS EVALUATION**
**REMEDIAL PROCESS OPTIMIZATION**
**OU1, HILL AFB, UTAH**

| | |
|---|---|
| Current Plume Width | 1,500 ft |
| Current Plume Length | 2,000 ft |
| Seepage Velocity | 3,289 ft/yr |
| Distance from Source to Downgradient Receptor | 3,000 ft |
| Distance from Source to Base Boundary | 2,800 ft |
| Distance from "Tail" of Plume to Downgradient Receptor | 1,000 ft |
| Distance from "Tail" of Plume to Base Boundary | 800 ft |
| Non-Aqeous-Phase Liquid (NAPL) Present? | No |
| Fluctuations in Groundwater Elevation? | Yes |
| Current Remediation System at Source? | None |

MAROS analysis. Wells that were not sampled in June 2000 were not included in the spatial analysis.

The MAROS tool incorporates the results of both the temporal and the spatial evaluations into the decision trees used to assess the relative value of data generated at individual monitoring points, and to identify monitoring points that may potentially provide redundant information, or information having relatively little value. By design, the decision trees used in the MAROS tool are conservative, such that the information generated using a particular monitoring point must provide information of little use in both the temporal and the spatial sense in order to be identified as redundant.

As a consequence of the conservative nature of the decision trees in the MAROS tool, only two wells were identified as potential candidates for elimination from the monitoring well network in the series of six simulations: well U1-115, completed in zone S1, and well U1-177, completed in zone A4 (Table 3.3). In the process of identifying a well for possible elimination, the MAROS decision trees require that the well must fail (provide redundant information) for each COC examined. By this standard, well U1-115 should remain in the monitoring network because the results of the first simulation for the S1 network (in which 1,1-DCA, 1,2-DCA, benzene, chlorobenzene, and cis-1,2-DCE were examined [Table 3.1]) did not generate a similar recommendation that this well should be eliminated (Table 3.3). If a smaller number of COCs were had been evaluated, the number of monitoring points recommended for elimination could potentially be greater.

**TABLE 3.3**
**RESULTS OF MONITORING PROGRAM EVALUATION USING MAROS TOOL**
**REMEDIAL PROCESS OPTIMIZATION**
**OU1, HILL AFB, UTAH**

| Water-Bearing Zone | Wells Removed from Program? |
|---|---|
| S1(1st Simulation) | None |
| S1(2nd Simulation) | U1-115 |
| A1 | None |
| A2 | None |
| A3/T1 | None |
| A4 | U1-177 |

### 3.2.2 Statistical Evaluation Using More Rigorous Techniques

Examination of the structure and function of the MAROS tool identified potential limitations to the usefulness of the software in groundwater monitoring evaluations. For example, inspection of the summary statistics of the groundwater monitoring data at Hill AFB OU1 (Table 2.1) indicates that a significant percentage of the results (more than 90 percent, depending upon the COC) consist of values that were below a detection limit. Even though these results are reported as "Not Detected," there is still some value associated with such results, and they must somehow be considered for a thorough evaluation of the monitoring program.

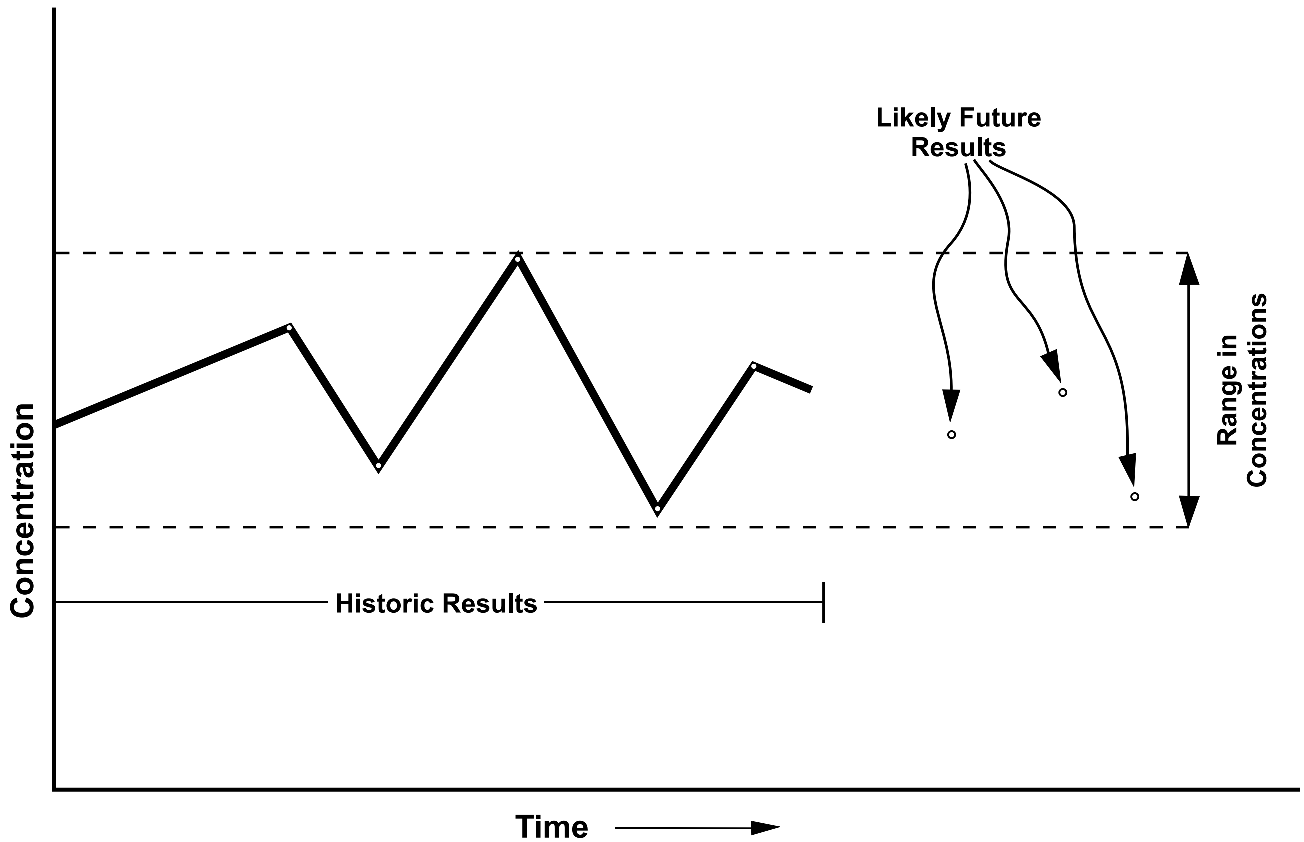
The MAROS tool assigns the value of the detection limit or the laboratory reporting limit to analytical results reported as "Not Detected." This convention potentially can generate misleading results in the temporal evaluation of monitoring data from a particular monitoring point. Consider a monitoring well that has been sampled routinely through some period of time. Groundwater samples from the well have been analyzed for TCE, and the analytical results have consistently been reported as "Not Detected." As noted previously, analytical methods and protocols have undergone a number of changes through the years, and these improvements have generally resulted in lower detection limits. At the inception of monitoring (mid-1980s), the detection limit for TCE in groundwater samples from the well may have been 5 μg/L, using EPA Method E601. With the introduction of more sophisticated gas-chromatographic (GC) and mass-spectrometric (MS) analytical methods (e.g., EPA Method SW 8240), the detection limit for TCE was lowered, perhaps to 1 μg/L. Current method detection limits for TCE in groundwater, using EPA Method SW8260B, are 0.5 μg/L to 0.2 μg/L. Consistent substitution of the analytical detection limit for a value reported as "Not Detected" (as the MAROS software does) will result in the identification of an apparently decreasing temporal trend in chemical concentrations through time, when in fact no such trend exists. The supposed "trend" is merely an artifact of the decreases in analytical detection limits through time.

This limitation was regarded as potentially serious. Furthermore, it was Parsons ES's opinion that the methods implemented in the MAROS software to examine spatial information were relatively simplistic; and the decision trees used to identify potentially redundant monitoring points and to evaluate the relative worth of monitoring information, may be overly conservative. Based on these considerations, Parsons ES applied more rigorous statistical procedures to the groundwater monitoring data from Hill AFB OU1 to further assess the results generated using the MAROS tool. The significance of temporal and spatial trends and the results of more rigorous analyses are described in the following subsections.

#### 3.2.2.1 Rigorous Assessment of Temporal and Spatial Trends

The value of information obtained from periodic monitoring at a particular monitoring well depends on the location of the well within (or outside of) the contaminant plume, the location of the well with respect to potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. The amount and quality of information obtainable at a particular monitoring point must be adequate to achieve the primary temporal and spatial objectives (Section 3.2) of a groundwater monitoring program. For example, the continued occurrence of a contaminant in groundwater at estimated concentrations below the clean-up goal at a monitoring location provides no information about temporal trends in contaminant concentrations, or about the extent to which contaminant migration is occurring, unless the monitoring location lies along a groundwater flowpath between a contaminant source and a potential receptor exposure point. Therefore, a monitoring well having a history of contaminant concentrations below clean-up goals may be providing no useful information in a groundwater monitoring program, depending on its location.

A trend of increasing contaminant concentrations in groundwater at a location between a contaminant source and a potential receptor exposure point may represent information critical in evaluating whether contaminants may migrate to the exposure point, thereby completing an exposure pathway. Identification of a trend of decreasing contaminant concentrations at the same location may be useful in evaluating decreases in a plume's areal extent, but does not represent information that is critical to the protection of a potential receptor. Similarly, a trend of decreasing contaminant concentrations in groundwater near a contaminant source may represent important information regarding the progress of remediation near, and downgradient of the source, while identification of a trend of increasing contaminant concentrations at the same location does not provide as much useful information regarding contaminant conditions. By contrast, the absence of a temporal trend in contaminant concentrations at a particular location within, or downgradient of a plume, indicates that virtually no additional information can be obtained by continued monitoring of groundwater at that location because the results of continued monitoring through time are likely to fall within the historic range of concentrations that have already been detected (Figure 3.3). Continued monitoring at locations where no temporal trend in contaminant concentrations is present serves merely to confirm the results of previous monitoring activities at that location. The relative amounts of information generated by the results of temporal trend evaluation at monitoring points near, upgradient of, and downgradient from contaminant sources are presented schematically as follow:




Source: Wiedemeier and Haas, 1999.

FIGURE 3.3

**CONCEPTUAL REPRESENTATION OF CONTINUED MONITORING AT LOCATION WHERE NO TEMPORAL TREND IN CONCENTRATIONS IS PRESENT**

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**Monitoring Point Near Contaminant Source**

| | |
|---|---|
| Relatively less information | Nondetect or no trend |
| | Increasing trend in concentrations |
| Relatively more information | Decreasing trend in concentrations |

**Monitoring Point Upgradient from Contaminant Source**

| | |
|---|---|
| Relatively less information | Nondetect or no trend |
| | Decreasing trend in concentrations |
| Relatively more information | Increasing trend in concentrations |

**Monitoring Point Downgradient from Contaminant Source**

| | |
|---|---|
| Relatively less information | Decreasing trend in concentrations |
| | Nondetect or no trend |
| Relatively more information | Increasing trend in concentrations |

#### 3.2.2.2 Rigorous Temporal Trend Analysis

The monitoring results for each of the COCs detected in each well completed in the seven monitoring zones at OU1, and active in the current monitoring program, were examined for temporal trends using the Mann-Kendall test. The objective of the evaluation was to identify those wells having increasing or decreasing concentration trends for each COC, and to consider the quality of information represented by the existence or absence of concentration trends in terms of the location of each monitoring point.

Summary results of Mann-Kendall temporal trend analyses for representative COCs are presented in Table 3.4. As implemented, the algorithm used to evaluate trends assigned a value of "Not Detected" to those constituents at concentrations that were consistently below analytical detection limits through time, rather than using detection-limit values that could generate potentially-misleading and anomalous "trends" in concentration. Color-coding of the table entries denotes the presence/absence of temporal trends, and allows those monitoring points having nondetectable concentrations, decreasing or increasing concentrations, or no discernible trend in concentrations to be readily identified. Monitoring points where chemical concentrations display no discernible temporal trend generally represent points providing the least amount of useful information. Depending on the monitoring location, locations consistently showing nondetected concentrations through time may also be contributing relatively little information. Monitoring points at which one or more of the COCs display increasing or

**TABLE 3.4**
**RESULTS OF TEMPORAL TREND ANALYSIS OF COC[a/] CONCENTRATIONS IN CURRENT GROUNDWATER MONITORING NETWORK**
**REMEDIAL PROCESS OPTIMIZATION, OU1**
**HILL AIR FORCE BASE, UTAH**

**Monitoring Zone S1**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB[b/] | 1,4-DCB[c/] | 1,1-DCA[d/] | 1,2-DCA[e/] | cis-1,2-DCE[f/] | trans-1,2-DCE[g/] | Toluene | 1,2,4-TCB[h/] | 1,1,1-TCA[i/] | TCE[j/] | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-006A | ND | ND | <4 meas | <4 meas | <4 meas | <4 meas | no trend | | ND | no trend | - | no trend | <4 meas |
| U1-006R | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-008R | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-021R | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-023R | <4 meas | no trend | no trend | + | <4 meas | <4 meas | <4 meas | | no trend | no trend | ND | + | no trend |
| U1-025A | <4 meas | <4 meas | | | <4 meas | <4 meas | | | <4 meas | | <4 meas | <4 meas | <4 meas |
| U1-027R | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-030R | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-041R | ND | no trend | no trend | + | ND | ND | no trend | | no trend | no trend | ND | ND | no trend |
| U1-044 | no trend | no trend | no trend | <4 meas | <4 meas | <4 meas | | | no trend | | + | ND | <4 meas |
| U1-046 | ND | ND | ND | <4 meas | ND | ND | | | ND | | ND | no trend | ND |
| U1-049 | ND | ND | ND | ND | ND | ND | <4 meas | | no trend | <4 meas | ND | ND | ND |
| U1-051 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-053 | ND | ND | ND | ND | ND | ND | <4 meas | | ND | no trend | - | ND | ND |
| U1-054 | ND | <4 meas | <4 meas | <4 meas | no trend | ND | | | <4 meas | | no trend | <4 meas | <4 meas |
| U1-064 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-065 | ND | no trend | - | no trend | - | ND | - | | - | + | - | ND | no trend |
| U1-067 | ND | no trend | no trend | no trend | no trend | ND | <4 meas | | ND | <4 meas | ND | no trend | no trend |
| U1-068 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-069 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-072 | no trend | - | - | - | no trend | no trend | <4 meas | | - | no trend | - | - | + |
| U1-073 | no trend | no trend | ND | no trend | - | no trend | <4 meas | | - | no trend | - | ND | + |
| U1-074 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-078 | ND | - | - | - | no trend | ND | - | | no trend | - | - | no trend | ND |
| U1-081 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | | <4 meas | <4 meas | <4 meas |
| U1-089 | - | + | no trend | + | no trend | - | - | | - | + | ND | no trend | - |
| U1-093R | ND | ND | ND | ND | ND | ND | ND | | + | - | ND | ND | ND |
| U1-100 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-101 | no trend | ND | - | - | - | no trend | no trend | | no trend | no trend | - | no trend | - |
| U1-102 | - | no trend | - | no trend | ND | no trend | - | | no trend | - | ND | ND | no trend |
| U1-107 | - | + | no trend | + | + | no trend | - | | - | - | ND | - | no trend |
| U1-115 | ND | ND | ND | ND | ND | ND | no trend | | ND | - | ND | no trend | ND |
| U1-116 | ND | no trend | no trend | ND | ND | ND | - | | no trend | - | ND | ND | ND |
| U1-118 | <4 meas | no trend | no trend | ND | ND | <4 meas | - | | no trend | <4 meas | ND | ND | no trend |
| U1-130 | ND | no trend | no trend | no trend | no trend | ND | - | | no trend | <4 meas | no trend | ND | no trend |
| U1-132 | ND | ND | no trend | + | - | ND | - | | - | no trend | - | - | ND |
| U1-140 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | | <4 meas | <4 meas | <4 meas |
| U1-143 | <4 meas | + | no trend | ND | <4 meas | ND | <4 meas | | no trend | <4 meas | ND | no trend | + |
| U1-166 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-169 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-174 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-175 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-201 | ND | - | no trend | no trend | - | ND | no trend | | - | no trend | - | no trend | + |
| U1-202 | ND | no trend | + | no trend | no trend | ND | - | | - | no trend | - | no trend | + |
| U1-203 | - | + | + | + | - | ND | - | | + | + | no trend | no trend | no trend |
| U1-204 | - | no trend | ND | no trend | - | no trend | - | | - | no trend | - | no trend | - |
| U1-205 | + | + | + | + | + | ND | ND | | + | - | ND | ND | + |
| U1-206 | ND | + | + | + | - | no trend | no trend | | + | no trend | ND | no trend | no trend |
| U1-207 | no trend | + | no trend | + | no trend | no trend | no trend | | no trend | - | ND | no trend | + |
| U1-208 | ND | no trend | no trend | no trend | no trend | ND | no trend | | no trend | - | ND | no trend | ND |
| U1-644 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-645 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-646 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-648 | | <4 meas | <4 meas | <4 meas | | | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-649 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1610 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1614 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1615 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1617 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1618 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1619 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |
| U1-1620 | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas | | <4 meas | <4 meas | <4 meas | <4 meas | <4 meas |

**Monitoring Zone A1**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB | 1,4-DCB | 1,1-DCA | 1,2-DCA | cis-1,2-DCE | trans-1,2-DCE | Toluene | 1,2,4-TCB | 1,1,1-TCA | TCE | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-045R | | no trend | no trend | no trend | | | no trend | | | | | no trend | no trend |
| U1-055 | | <4 meas | <4 meas | <4 meas | | | | | | | | <4 meas | <4 meas |
| U1-056 | | ND | <4 meas | <4 meas | | | <4 meas | | | | | ND | ND |
| U1-057 | | ND | ND | ND | | | <4 meas | | | | | ND | ND |
| U1-058 | | <4 meas | <4 meas | <4 meas | | | | | | | | <4 meas | <4 meas |
| U1-063 | | - | no trend | no trend | | | ND | | | | | ND | + |
| U1-077R | | ND | ND | ND | | | ND | | | | | ND | no trend |
| U1-092 | | no trend | no trend | no trend | | | - | | | | | no trend | no trend |
| U1-103 | | ND | no trend | ND | | | no trend | | | | | no trend | ND |
| U1-117 | | ND | ND | ND | | | ND | | | | | ND | ND |
| U1-119 | | no trend | no trend | no trend | | | + | | | | | ND | + |
| U1-125 | | ND | ND | ND | | | ND | | | | | ND | ND |
| U1-126 | | ND | ND | ND | | | ND | | | | | ND | ND |
| U1-144 | | no trend | no trend | ND | | | ND | | | | | ND | ND |
| U1-162 | | no trend | ND | no trend | | | - | | | | | ND | no trend |
| U1-165 | | <4 meas | <4 meas | <4 meas | | | <4 meas | | | | | <4 meas | <4 meas |
| U1-168 | | <4 meas | <4 meas | <4 meas | | | <4 meas | | | | | <4 meas | <4 meas |
| U1-647 | | ND | ND | ND | | | no trend | | | | | ND | ND |
| U1-667 | | no trend | no trend | no trend | | | no trend | | | | | no trend | no trend |

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**TABLE 3.4 (Continued)**
**RESULTS OF TEMPORAL TREND ANALYSIS OF COC[a/] CONCENTRATIONS IN CURRENT GROUNDWATER MONITORING NETWORK**
**REMEDIAL PROCESS OPTIMIZATION, OU1**
**HILL AIR FORCE BASE, UTAH**

**Monitoring Zone A2**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB | 1,4-DCB | 1,1-DCA | 1,2-DCA | cis-1,2-DCE | trans-1,2-DCE | Toluene | 1,2,4-TCB | 1,1,1-TCA | TCE | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-038 | | | | | | ND | | | | | | ND | ND |
| U1-043 | | | | | | + | no trend | | | | | ND | + |
| U1-079 | | | | | | <4 meas | no trend | | | | | no trend | + |
| U1-082 | | | | | | ND | no trend | | | | | ND | ND |
| U1-083 | | | | | | - | ND | | | | | - | ND |
| U1-086 | | | | | | ND | ND | | | | | ND | ND |
| U1-091 | | | | | | ND | ND | | | | | ND | ND |
| U1-104 | | | | | | no trend | - | | | | | no trend | no trend |
| U1-120 | | | | | | ND | ND | | | | | ND | ND |
| U1-139 | | | | | | ND | ND | | | | | ND | ND |
| U1-141 | | | | | | ND | - | | | | | ND | ND |
| U1-142 | | | | | | ND | ND | | | | | ND | ND |
| U1-161 | | | | | | <4 meas | <4 meas | | | | | <4 meas | <4 meas |
| U1-164 | | | | | | <4 meas | <4 meas | | | | | <4 meas | <4 meas |
| U1-167 | | | | | | <4 meas | <4 meas | | | | | <4 meas | <4 meas |

**Monitoring Zone A3**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB | 1,4-DCB | 1,1-DCA | 1,2-DCA | cis-1,2-DCE | trans-1,2-DCE | Toluene | 1,2,4-TCB | 1,1,1-TCA | TCE | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-090 | | | | | | | - | ND | | | | - | ND |
| U1-105 | | | | | | | no trend | + | | | | no trend | + |
| U1-138 | | | | | | | - | no trend | | | | - | + |
| U1-151 | | | | | | | + | + | | | | no trend | no trend |
| U1-152 | | | | | | | ND | ND | | | | ND | ND |
| U1-153 | | | | | | | <4 meas | <4 meas | | | | <4 meas | <4 meas |
| U1-173 | | | | | | | <4 meas | <4 meas | | | | <4 meas | <4 meas |
| U1-193 | | | | | | | <4 meas | <4 meas | | | | <4 meas | <4 meas |

**Monitoring Zone T1**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB | 1,4-DCB | 1,1-DCA | 1,2-DCA | cis-1,2-DCE | trans-1,2-DCE | Toluene | 1,2,4-TCB | 1,1,1-TCA | TCE | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-097 | | | | | | | - | | | | | - | |
| U1-098 | | | | | | | - | | | | | no trend | |
| U1-099 | | | | | | | + | | | | | + | |
| U1-108 | | | | | | | no trend | | | | | no trend | |
| U1-112 | | | | | | | - | | | | | - | |
| U1-154 | | | | | | | no trend | | | | | no trend | |
| U1-176 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-179 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-182 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-184 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-186 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-188 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-190 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-192 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1631 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1632 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1634 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1635 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1637 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1639 | | | | | | | <4 meas | | | | | <4 meas | |
| U1-1640 | | | | | | | <4 meas | | | | | <4 meas | |

**Monitoring Zone A4**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB | 1,4-DCB | 1,1-DCA | 1,2-DCA | cis-1,2-DCE | trans-1,2-DCE | Toluene | 1,2,4-TCB | 1,1,1-TCA | TCE | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-094 | | | | | | | | | | | | ND | |
| U1-095 | | | | | | | | | | | | ND | |
| U1-096 | | | | | | | | | | | | ND | |
| U1-113 | | | | | | | | | | | | no trend | |
| U1-155 | | | | | | | | | | | | ND | |
| U1-155R | | | | | | | | | | | | <4 meas | |
| U1-177 | | | | | | | | | | | | <4 meas | |
| U1-180 | | | | | | | | | | | | <4 meas | |
| U1-183 | | | | | | | | | | | | <4 meas | |
| U1-185 | | | | | | | | | | | | <4 meas | |
| U1-187 | | | | | | | | | | | | <4 meas | |
| U1-189 | | | | | | | | | | | | <4 meas | |
| U1-191 | | | | | | | | | | | | <4 meas | |
| U1-194 | | | | | | | | | | | | <4 meas | |
| U1-195 | | | | | | | | | | | | <4 meas | |
| U1-1636 | | | | | | | | | | | | <4 meas | |

**Monitoring Zone A5**

| Well ID | Benzene | Chlorobenzene | 1,2-DCB | 1,4-DCB | 1,1-DCA | 1,2-DCA | cis-1,2-DCE | trans-1,2-DCE | Toluene | 1,2,4-TCB | 1,1,1-TCA | TCE | Vinyl Chloride |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U1-156 | | | | | | | | | | | | | |
| U1-178 | | | | | | | | | | | | | |
| U1-181 | | | | | | | | | | | | | |
| U1-198 | | | | | | | | | | | | | |

| | |
|---|---|
| ND | = Constituent has not been detected in well monitoring history. |
| no trend | = No statisitically significant temporal trend in concentrations. |
| + | = Statistically significant increasing trend in concentrations. |
| - | = Statistically significant decreasing trend in concentrations. |
| < 4 meas | = Fewer than four measurements at the monitoring well. |
| | = No data available for the monitoring well; or chemical is not a COC. |

[a/] COC = chemical of potential concern.
[b/] 1,2-DCB = 1,2-dichlorobenzene.
[c/] 1,4-DCB = 1,4-dichlorobenzene.
[d/] 1,1-DCA = 1,1-dichloroethane.
[e/] 1,2-DCA = 1,2-dichloroethane.
[f/] cis-1,2-DCE = cis-1,2-dichloroethene.
[g/] trans-1,2-DCE = trans-1,2-dichloroethene.
[h/] 1,2,4-TCB = 1,2,4-trichlorobenzene.
[i/] 1,1,1-TCA = 1,1,1-trichloroethane.
[j/] TCE = trichloroethene.

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decreasing temporal trends in concentrations represent points at which monitoring should be continued.

Monitoring points in zone S1 display the greatest number of increasing concentration trends (red color-coding in Table 3.4) in all the water-bearing units. However, eight monitoring wells completed in zone S1 display consistent “Not Detected” values, decreasing trends in concentration, or “no trend” for all COCs, indicating that these monitoring locations should be evaluated in greater detail, and considered for abandonment or retention in the network. Numerous other wells are newly installed, or have only been sampled infrequently. Fewer than four analytical results are available for these wells, and no determination can be made regarding the presence or absence of temporal trends in COC concentrations at these locations. Monitoring should be continued at these locations until sufficient information has been generated to evaluate temporal concentration trends. Similar considerations apply to monitoring points completed in the other water-bearing zones (Table 3.4).

#### 3.2.2.3 Rigorous Spatial Trend Analysis

Spatial monitoring data available for OU1 were also examined using geostatistical techniques. *Geostatistics*, or the Theory of Regionalized Variables (Clark, 1987; Rock 1988; American Society of Civil Engineers [ASCE], 1990a and 1990b), is concerned with variables having values dependent on location, and that are continuous in space, but which vary in a manner too complex for simple mathematical description. Geostatistics is based on the premise that the differences in values of a spatial variable depends only on the distances between sample locations, and the relative orientations of sample locations -- that is, the values of a variable (e.g., chemical concentrations) measured at two locations that are spatially "close together" will be more similar than values of that variable measured at two locations that are "far apart."

Ideally, application of geostatistical methods to the results of the OU1 groundwater monitoring program could be used to estimate chemical concentrations at every point within the OU1 plume, and could also be used to generate estimates of the “error,” or uncertainty associated with each concentration value. Therefore, the monitoring program could be “optimized” by using available information to identify those areas associated with the greatest uncertainty. Conversely, sampling points could be successively eliminated from simulations, and the resulting uncertainty examined, to evaluate if significant loss of information (represented by increasing error or uncertainty in estimated chemical concentrations) occurs as the number of sampling points is reduced. Repeated application of geostatistical estimating techniques, using tentatively identified sampling locations, could then be used to generate a sampling program that would provide an acceptable level of uncertainty regarding chemical distribution with the minimum possible number of samples collected. Furthermore, application of geostatistical methods can provide unbiased representations of the distribution of chemicals at different locations in the subsurface, enabling the extent of chemicals to be evaluated more accurately and effectively.

Fundamental to geostatistics is the concept of semivariance [$\gamma(h)$], a measure of the spatial dependence between samples (e.g., chemical concentrations) in a specified direction. Semivariance is defined for a constant spacing between samples ($h$) as:

$$\gamma(h) = \frac{1}{2n} \sum [g(x) - g(x + h)]^2 \qquad \text{Eq. 1}$$

where

$\gamma(h)$ = semivariance calculated for all samples at a distance $h$ from each other;

$g(x)$ = value of the variable in sample at location $x$;

$g(x + h)$ = value of the variable in sample at a distance $h$ from sample at location $x$; and

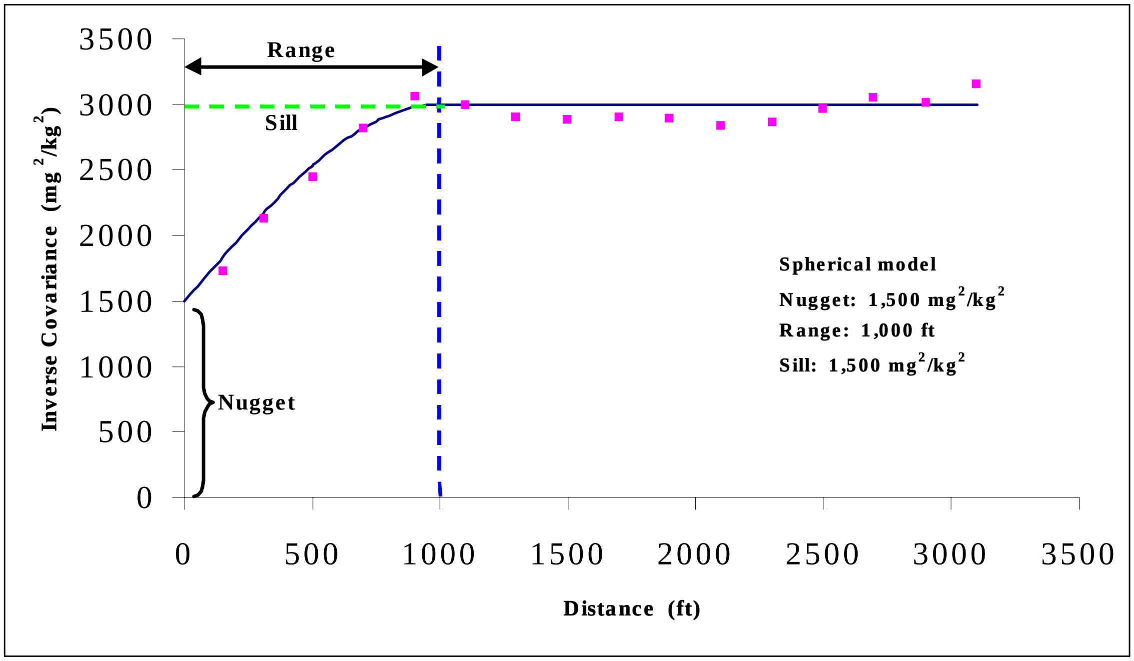
$n$ = number of samples in which the variable has been determined.

Semivariograms (plots of $\gamma(h)$ versus $h$) are a means of depicting graphically the range of distances over which, and the degree to which, sample values at a given point are related to sample values at adjacent, or nearby, points; and conversely, indicate how close together sample points must be for a value determined at one point to be useful in predicting unknown values at other points. For $h = 0$, for example, a sample is being compared with itself, so normally $\gamma(0) = 0$ (the semivariance at a spacing of zero, is zero), except where a so-called nugget effect is present (Figure 3.4), which implies that sample values are highly variable at distances less than the sampling interval. As the distance between samples increases, sample values become less and less closely related, and the semivariance, therefore, also increases, until a sill is eventually reached, where $\gamma(h)$ equals the overall variance (i.e., the variance around the average value). The sill is reached at a sample spacing called the range of influence, beyond which sample values are not related. We can only predict values between points at spacings less than the range of influence; but within that distance, the semivariogram provides the proper weightings, which apply to sample values separated by different distances.

When a semivariogram is calculated for a variable over an area (e.g., concentrations of cis-1,2-DCE at locations in the S1 water-bearing unit throughout OU1), an irregular spread of points across the semivariogram plot is the usual result (Rock, 1988). One of the most subjective tasks of geostatistical analysis is to identify a continuous, theoretical semivariogram model that most closely follows the real data. Fitting a theoretical model to calculated semivariance points is accomplished by trial-and-error, rather than by a formal statistical procedure (Davis, 1986; Clark, 1987; Rock, 1988). If a "good" model fit results, then $\gamma(h)$ [the semivariance] can be confidently estimated for any value of $h$, and not only at the sampled points.

Because cis-1,2-DCE is generally the most widespread COC at Hill AFB OU1, the initial spatial evaluation of monitoring data focused on this constituent. The greatest number of monitoring points at OU1 are completed in zone S1; therefore, the distribution of cis-1,2-DCE in zone S1 was examined. The commercially-available geostatistical software package GEO-EAS (Englund and Sparks, 1992), developed by the USEPA, was used to calculate semivariograms for cis-1,2-DCE in groundwater of zone S1. Lag spacings on the order of 250 feet (approximately the average spacing between wells at OU1) were initially used to develop the semivariograms. A total of 435 sample pairs was used in calculations.

**Figure 3.4 Idealized Semivariogram Model**

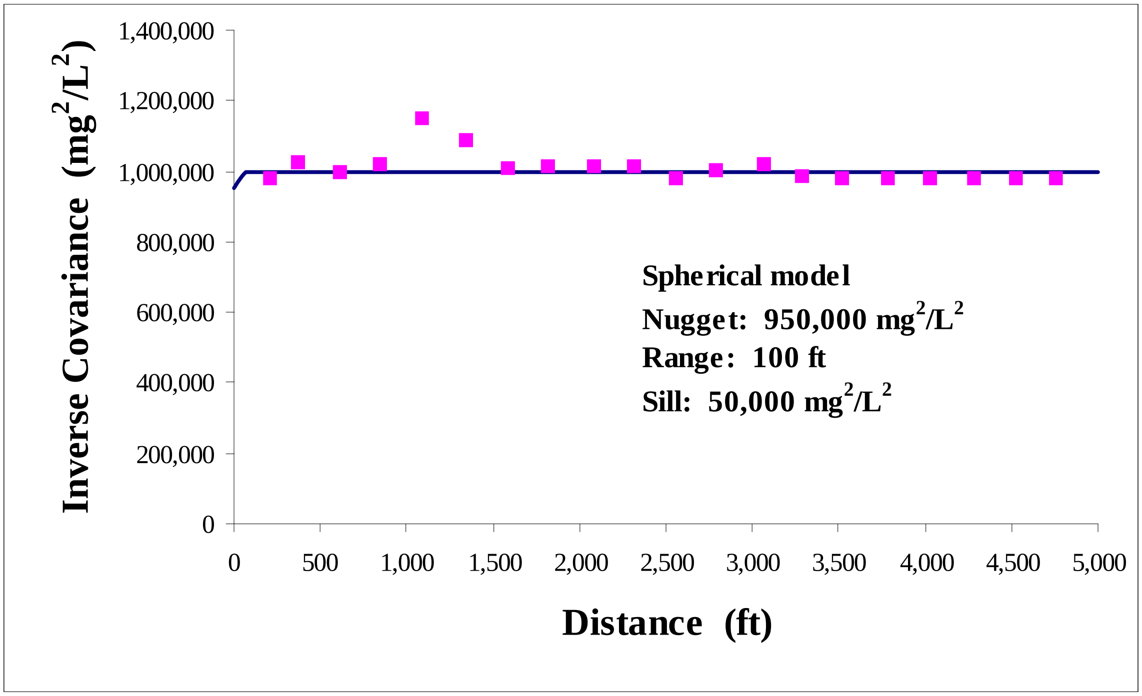



Semivariogram models were originally calculated for cis-1,2-DCE using the semivariance, as defined in Equation 1. Considerable scatter of the data was apparent as models were fitted. Accordingly, an alternate form of the semivariogram – the non-ergodic variogram (Deutsch and Journel, 1998; Englund and Sparks, 1992) was used (Figure 3.5). Rather than being based on semivariance, as are classical semivariograms (Equation 1), non-ergodic variograms are based on consideration of the changes in inverse covariance of sample results with changes in sample spacing (Englund and Sparks, 1992). Variograms of this type can be less sensitive to outliers, skewed distributions, or clustered data than classical semivariograms, and may enable the underlying spatial structure of the data to be recognized and described in cases where an ordinary semivariogram is too noisy. Non-ergodic variograms have the same units (in this case, $\mu g^2/L^2$) as ordinary semivariograms, and can be modeled and used in the same manner as ordinary variograms.

After considerable trial-and-error, it was determined that the population of semi-variogram models that could be developed for cis-1,2-DCE in groundwater of zone S1 at OU1 consisted exclusively of pure nugget – that is, the model does not pass through the origin of the graph, but rather begins at a point some distance up the ***y*** ("inverse covariance") axis (Figure 3.5). The occurrence of a "nugget" is indicative of a regionalized variable that varies over distances less than the sampling interval. In each model representation, the nugget moves directly into an elevated sill, which represents that value of the variance at which variation between sample values becomes random, and the sample values are no longer statistically related.

Because the occurrence of the nugget effect and elevated sills indicated that the spatial variation in COC concentrations appears to be random, at least on the scale at which sampling has occurred (represented by the average spacing between monitoring wells), it was concluded that the underlying spatial structure of chemical concentration

**Figure 3.5 Non-Ergodic Semivariogram Model of cis-1,2-DCE Concentrations**




data at Hill AFB OU1 could not be represented by semivariogram models. Further application of rigorous geostatistical techniques was not attempted. The apparently random nature of the spatial distribution of COCs in groundwater at Hill AFB OU1 may be a consequence of the manner that COCs move in groundwater off of the bluff, and into the groundwater system of the Weber River Valley (Section 2.2.5), or may result from some other, unidentified process.

### 3.2.2.4 Summary of the Rigorous Temporal and Spatial Trend Analysis

The application of the methodologies for qualitative analysis of the monitoring network and the more rigorous Mann-Kendall analysis are viable procedures to perform for the evaluation steps identified in the decision-trees in Section 5.2 of the PSVP. However, Parsons ES suggests reliance on the simple spatial evaluation techniques provided in the MAROS tool (i.e., Delauney triangles) to address the spatial aspects of the monitoring program.

# SECTION 4

# RECOMMENDATIONS

The approach used to evaluate the PSVP, MAROS, and the LTMP for OU1 at Hill AFB was presented in Section 3. This section summarizes recommendations for modifications to the Draft PSVP, MAROS, and the LTMP based on the RPO evaluation.

## 4.1 RECOMMENDATIONS FOR THE PSVP

As discussed in Section 3.1, recommendations for modification of the Internal Draft PSVP (CH2M Hill, 1999a) include adding procedures and methodologies for statistical evaluations of groundwater monitoring data. In a letter report dated May 1, 2000 to Dr. Javier Santillan of AFCEE/ERT, Parsons ES provided several paragraphs for incorporation into the Internal Draft PSVP to address the statistical evaluation. The suggested text, provided in Appendix B, includes descriptions of statistical methods and procedures to be used in evaluating long-term monitoring data. The text was generated with the intent that it could be inserted directly into the Draft PSVP for OU1 at Hill AFB. Because the PSVP will become part of the administrative record for Hill AFB OU1, Parsons ES did not identify a specific software package (e.g., the MAROS tool) for evaluating groundwater monitoring data. A specific software package was not recommended for the following reasons.

- Because the PSVP for Hill AFB OU1 will become part of the administrative record, specification of a particular methodology (or software package) to be used in data evaluation generally means that all future data evaluation must be completed using that methodology (or software) and no other. Should the Base or its environmental contractors determine at any time that a specific software package was not appropriate for their needs, it would probably be necessary to obtain Explanation of Significant Differences (ESD) documentation, or similar, to enable the Base to discontinue use of the software.

- Recent discussions with the Base have indicated that Dr. Robert Gibbons has been retained to develop a statistical methodology for evaluating groundwater monitoring data. Therefore, it would be inappropriate to recommend the consistent use of any software package to evaluate monitoring data at Hill AFB OU1.

Based on these considerations, Parsons ES has provided only a general discussion of the types of statistical evaluations (temporal and spatial evaluations) to be completed using monitoring data from Hill AFB OU1 (Appendix B). Although the evaluations described in this report should be conducted periodically so that the trends in achieving cleanup objectives can be examined regularly, Parsons ES did not specify the frequency at which these evaluations should occur. The Base and its environmental contractors should establish the logic for determining the frequency of statistical evaluations in the PSVP. The frequency of evaluation will be subject to change, depending on the frequency of monitoring and the objectives of a particular evaluation.

## 4.2 RECOMMENDATIONS FOR MODIFICATION OF THE MAROS TOOL

Based on our evaluation of groundwater monitoring data using the MAROS tool (Section 3.2), Parsons ES identified several issues that should be addressed before MAROS becomes more widely distributed and used by the United States Air Force (USAF):

- There are difficulties associated with importing data from EXCEL™ files into MAROS. MAROS is designed to accept data in three formats: text files in ERPIMS format, Microsoft™Access® ERPMIS files, and EXCEL® files. However, Parsons ES personnel experienced difficulties with importing the EXCEL® files into the software, and ultimately reformatted the data as Access® ERPMIS files for use in MAROS. Re-formatting the data was a time-consuming process because the Access® ERPMIS format includes 4 tables with approximately 20 parameters each, while the EXCEL® format includes a single table with about 8 parameters.

- MAROS requires the designation of each well within a particular analysis as a "source" or "tail" well. While this information is important for the analysis, entering this information was a time-consuming step. For Hill AFB OU1, these designations were made only after searching through available plume maps for the locations of wells within the plume. It can be difficult to determine whether particular wells (such as background wells that are upgradient of the source or otherwise outside the plume boundary) should be designated as a "source" or "tail" location.

- MAROS results generated using the Mann-Kendall trend analyses were confusing in several cases. For example, the results from the Mann-Kendall analysis for TCE in four wells completed in zone A1 indicated that four different trends (No Trend, Decreasing, Probably Decreasing, and Stable) were present, depending upon the well. However, TCE concentrations in all four wells were below detection limits ("Not Detected") through the monitoring history of the wells. Even after consulting the user's manual, it was difficult to determine if this was a manifestation of a program bug, or if the program was applying different criteria to the four wells, leading to different results for each well.

- MAROS generates useful output summaries of results for each analysis (linear regression, Mann-Kendall, sampling optimization, etc.). However, these output reports cannot easily be saved to another file for reference at a later time. The entire analysis must be re-completed in order to generate a new set of reports. MAROS would be more user-friendly if the summary reports could be stored with the archived input data, so that additional simulations would not be necessary.

- The relatively small number of constituents (five) and wells (forty) that can be evaluated in a single analysis is a significant limitation of the MAROS software. The limit of five chemicals can be bypassed by simply repeating the analysis with a different set of chemicals. However, the limit of 40 wells, as necessary for the

Mann-Kendall test, is more problematic. For areas with more than 40 wells (e.g., zone S1 at OU1 with approximately 60 wells), the wells to be used in the evaluation must be pre-selected in advance of analysis. The monitoring locations cannot be divided into two or more groups, as this will affect the results of the spatial analysis. The well pre-selection process can be time-consuming, and the decision criteria used in selecting a subset of monitoring points may differ from or conflict with the MAROS methodology.

- MAROS requires that sampling dates for all wells in a sampling event be identical, otherwise the program does not recognize them as belonging to a single sampling event. The program does allow the user to combine wells with different sampling dates as an event. MAROS would be more user-friendly if it recognized that sampling dates within a user-defined period (e.g., two or three weeks) may be part of the same sampling event. Currently, this issue is best addressed when the MAROS input files are formated, and the database manager can identify the sampling events and manipulate the sampling dates (or event dates) accordingly.

## 4.3 RECOMMENDATIONS TO THE LTMP BASED ON MAROS

Based on the results of the MAROS analysis (Section 3.2), it is recommended that one well (U1-177) be eliminated from the long term monitoring program at Hill OU1. In addition, recommended sampling frequencies have been generated using the MAROS tool, for monitoring wells completed in each of the water-bearing zones. These are provided in the MAROS output results, provided in Appendix A.

## 4.4 CONCLUSIONS OF THE MORE RIGOROUS STATISTICAL EVALUATIONS

Depending on the future needs of Hill AFB, the more rigorous statistical procedures may be effectively applied to groundwater monitoring data at Hill AFB OU1. The methodologies and results of the more rigorous qualitative and Mann-Kendall temporal trend evaluation described in Section 3.2.2.2 could be incorporated into the monitoring decision trees developed for Hill AFB, and presented in the Draft PSVP. However, application of the more rigorous spatial statistical techniques is probably not warranted.

# SECTION 5

# REFERENCES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# APPENDIX A

# OUTPUT FROM THE MAROS TOOL USED IN THE ANALYSIS

This information is available upon request from
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# APPENDIX B

# RECOMMENDED TEXT FOR INCLUSION IN SECTION 5.2.4.2 OF DRAFT PSVP

The text provided below is recommended for inclusion in Section 5.2.4.2 of the Draft PSVP. References to be included in the bibliography section of the Draft PSVP are also provided.

### *5.2.4.2 Non-Source Area Natural Attenuation Monitoring.*

Long-term groundwater monitoring will be performed to evaluate natural attenuation within the Non-Source Area of OU1. Long-term groundwater monitoring programs have two primary objectives:

1. To evaluate the extent to which contaminant migration is occurring, particularly if a point of potential exposure of a susceptible population to the contaminant exists (*spatial evaluation*); and

2. To evaluate long-term temporal trends in contaminant concentrations at one or more points (*temporal evaluation*).

This section presents the statistical screening and evaluation procedures to meet the objectives of the monitoring program at the OU1 Non-Source Area. These procedures are in general agreement with monitoring algorithms recently developed by Cameron and Hunter (1999). The periodic evaluation and optimization of the existing monitoring network may also be conducted in accordance with the following guidance:

- Designing Monitoring Programs to Effectively Evaluate the Performance of Natural Attenuation (Wiedemeier and Haas, 1999).

- Long-Term Monitoring Optimization Guide (AFCEE, 1997).

If contaminant concentrations in the Non-Source Area groundwater plume are shown to decrease through time and the areal extent of the OU1 Non-Source Area plume becomes smaller following initiation of remediation activities in the Source Area and monitored natural attenuation in the Non-Source area, then natural attenuation processes will be assumed to be successful in satisfying the appropriate DQOs. In this event, monitoring of groundwater quality trends will continue until remediation goals are achieved. Monitoring will continue for a subsequent five-year period at reduced frequency, and using a smaller monitoring network, to be determined by concurrence of the BCT.

***Principles of Monitoring Program Design.*** Designing an effective groundwater monitoring program involves locating groundwater monitoring wells and developing a site-specific groundwater sampling and analysis strategy to maximize the amount of spatial and temporal information that can be obtained while minimizing incremental costs. An effective monitoring program will provide information regarding plume migration and changes in chemical concentrations through time, enabling decision-makers to verify that remediation is occurring at rates sufficient to achieve RAOs. The periodic evaluation of the monitoring program should include consideration of existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

Performance monitoring wells, located up-gradient, within, and just down-gradient from the plume provide a means of evaluating the effectiveness of the OU1 remedial action relative to performance criteria. Long-term monitoring of these wells also provides information about migration of the plume and temporal trends in chemical concentrations. Contingency monitoring wells down-gradient from the plume are used to ensure that the plume is not expanding past a point of compliance, and to trigger a contingency remedy if contaminants are detected. One of the most important purposes of the monitoring program is to confirm that the contaminant plume is behaving as predicted.

***Temporal Analyses.*** Temporal trends in contaminant concentrations will be used to evaluate the stability of the Non-Source Area plume, and to assess the extent to which natural attenuation processes are reducing contaminant concentrations in the Non-Source Area groundwater plume. Temporal trends analysis will also be used to determine the optimal periodicity (annual, semi-annual, quarterly) of the sampling events.

If removal of chemical mass is occurring in the subsurface as a consequence of natural attenuation processes or operation of the remediation system, mass removal will be apparent as a decrease in contaminant concentrations through time at a particular sampling location, as a decrease in contaminant concentrations with increasing distance from the OU1 Source Area, or as a change in the suite of chemicals through time or with increasing migration distance.

Temporal trends in chemical concentrations can be examined rigorously using various statistical procedures, including regression analyses and the Mann-Kendall test for trends. The Mann-Kendall non-parametric test (Gibbons, 1994) is well suited for application to the evaluation of environmental data because the sample size can be small (as few as five data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. If a trend is determined to be present, a non-parametric slope of the trend line (change per unit time) can also be estimated using the test procedure.

***Spatial Analyses.*** Spatial statistical techniques will be applied to assess the relative spatial value of data generated during monitoring, and to optimize monitoring networks. If appropriate, spatial monitoring data available for the OU1 Non-Source Area groundwater plume will be evaluated using geostatistical techniques. *Geostatistics*, or the Theory of Regionalized Variables (Clark, 1987; Rock 1988; American Society of Civil Engineers [ASCE], 1990a and 1990b), is concerned with variables having values dependent on location, and that are continuous in space, but which vary in a manner too complex for simple mathematical description. Geostatistics is based on the premise that the differences in values of a spatial variable depends only on the distances between sample locations, and the relative orientations of sample locations -- that is, the values of a variable (e.g., chemical concentrations) measured at two locations that are spatially "close together" will be more similar than values of that variable measured at two locations that are "far apart".

Ideally, application of geostatistical methods to the results of the groundwater monitoring program in the OU1 Non-Source Area plume can be used to estimate chemical concentrations at every point within the OU1 plume, and can also generate estimates of the *error*, or uncertainty associated with each concentration value.

Therefore, the monitoring program can be optimized by using available information to identify those areas having the greatest associated uncertainty. Conversely, sampling points can be successively eliminated from simulations, and the resulting uncertainty examined, to evaluate if significant loss of information (represented by increasing error or uncertainty in estimated chemical concentrations) occurs as the number of sampling points is reduced. Repeated application of geostatistical estimating techniques, using tentatively identified sampling locations, can then be used to generate a sampling program that would provide an acceptable level of uncertainty regarding contaminant distribution, with the minimum possible number of samples collected. This can be compared periodically with the existing program. Furthermore, application of geostatistical methods can provide unbiased representations of the distribution of contaminants at different locations in the subsurface, enabling the extent of contaminants, and changes in the spatial distribution of contaminants through time, to be evaluated more accurately and effectively. As appropriate, the groundwater monitoring data will be examined periodically using standard geostatistical methods (variogram analysis, kriging) and commercially available software (e.g., GeoEAS; Englund and Sparks, 1992).

If the areal extent of the Non-Source Area groundwater plume increases in size, or if the extent of the plume increases significantly in the down-gradient direction, supplemental groundwater monitoring will be completed to confirm the increase in size or down-gradient extent. Additional confirmatory monitoring will entail collection of additional groundwater samples in accordance with established criteria through an additional 12-month period. Groundwater monitoring data will be reevaluated after the 12-month period, in accordance with procedures described above. Potential impacts associated with the Non-Source Area groundwater plume will be reviewed in light of the estimated time required for groundwater restoration.

### *References to be inserted into the Bibliography of the PSVP*

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# APPENDIX C

# MAROS SOFTWARE AND USERS MANUAL

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